Analogical reasoning and its development : role of executive functions and the goal of the task

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THÈSE

Pour obtenir le grade de

Docteur de l'Université de Bourgogne

Discipline: Psychologie

par

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16 décembre 2013

Raisonnement par analogie et son développement: rôle des fonctions exécutives et du but de la tâche

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À A.D. et T.S.

Remerciements

A Jean-Pierre Thibaut et Bob French, merci d'avoir guidé mes premiers pas dans la recherche en psychologie, de m'avoir fait confiance et soutenu durant ces trois années, ainsi que d'avoir su cultiver en moi le goût du savoir.

Je tiens également à remercier les membres de mon jury, Agnès Blaye, Jean-Michel Boucheix, et James Hampton et Philippe Monneret pour m'avoir fait l'honneur de leur présence en ce jour, et de m'avoir apporté leurs conseils et remarques avisés sur le contenu de ce manuscrit.

Merci à mes parents et ma famille, ainsi que mes amis et les membres du LEAD pour avoir mis en place un contexte et une ambiance agréable tout au long de mon doctorat. Sans eux, ces trois années n'auraient pas parues aussi courtes sous le ciel (le plus souvent) gris de Dijon.

Enfin, j'aimerai remercier tout spécialement ceux sans qui ce travail n'aurait pas pu être mené à bien. Un grand merci aux responsables des écoles élémentaires et maternelles qui ont bien voulu me faire confiance et m'accueillir, ainsi qu'à tous les participants, enfants et adultes, qui ont donné de leur temps pour me permettre de faire avancer les travaux présentés ici.

Résumé

Le présent manuscrit développe une problématique liée à l'implication des capacités de gestion de buts et d'engagement des fonctions exécutives dans le raisonnement par analogie et son développement. Les trois premières expériences étudient cette problématique dans deux tâches de raisonnement par analogie différentes à travers l'étude des stratégies visuelles employées par des adultes et des enfants de 6-7 ans. Les résultats montrent des différences de stratégies visuelles entre les tâches, liées aux buts différents de celles-ci, ainsi que, entre enfants et adultes, des différences de patterns visuels liés à l'inhibition de l'information non pertinente pour la résolution des problèmes. Les deux expériences suivantes étudient les stratégies visuelles, toujours en lien avec le fonctionnement exécutif et le maintien du but, dans une tâche A:B::C:? dont la difficulté est manipulée afin de mettre en évidence des différences d'engagement de processus de contrôle et d'évaluation. Les résultats montrent un effet de la difficulté des essais, ainsi que du type de distracteur, dans les stratégies visuelles. Enfin les trois dernières expériences étudient l'implication de la flexibilité cognitive, une des fonctions exécutives, dans le raisonnement par analogie, chez l'enfant (5-6 ans), limité dans sa flexibilité. Les résultats montrent que l'ancrage dans un type de représentation, pertinent ou non pour la solution du problème, est lié à leur capacité à résoudre le problème, et suggèrent une difficulté à changer de représentation au cours de la résolution. Ces résultats sont finalement discutés en rapport aux modèles de raisonnement par analogie et de développement de cette capacité.

Mots-clés: raisonnement par analogie; fonctions exécutives; gestion du but; eye-tracking; stratégies

Abstract

This manuscript develops an issue related to the involvement of goal management capabilities and executive functions in this type of reasoning and its development. The first three experiments examine this issue in two tasks of analogical reasoning, the scene analogy task and the A:B::C:? task, through the study of visual strategies used by adults and children aged 6-to-7. The results show differences in visual patterns related to goals, and to the inhibition of irrelevant information for the solution of the problems, between the different tasks, and between children and adults. The following two experiments study the visual strategies, always in relation to executive functioning and goal management, in an A:B::C:? task whose difficulty is manipulated to highlight the difference in involvement of monitoring and evaluation processes. The results do show an effect of the difficulty of the test and the type of distractor in the visual strategies employed. Finally, the last three experiments investigate the involvement of cognitive flexibility, one of the executive functions, in the analogical reasoning of preschool children (5-6-year-olds), limited in their flexibility. The results show that their early anchoring in a type of representation, relevant or not to the solution of the problem, is related to their ability to solve the problem later, and thus suggest a difficulty in shifting their representation during the resolution of the problems. These results are finally discussed in relation to models of analogical reasoning and of the development of this ability, especially those integrating goal management and executive functions.

Keywords: analogical reasoning; executive functions; goal management; eye-tracking; cognitive flexibility; strategies

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I. Introduction théorique

Le premier chapitre de la thèse est consacré à la revue de la littérature dans le domaine du raisonnement par analogie et de son développement, ainsi que des principaux modèles et théories rendant compte des phénomènes observés empiriquement dans cette littérature. Nous commençons par définir le raisonnement par analogie comme étant le processus de comparaison de la similarité entre les structures relationnelles de deux domaines: le domaine source qui dirige l'analogie, et le domaine cible qui est souvent moins complètement représenté et qui fera alors l'objet d'inférence sur la base de la structure relationnelle du domaine source (Gentner, 1983). L'analogie doit être distinguée, du fait qu'elle résulte purement sur la structure relationnelle entre les éléments composant les domaines et non sur des caractéristiques de surface, de ce que Gentner (1989) appelle la similarité de pure apparence (*mere appearance*) qui résulte de la ressemblance des propriétés de surface des domaines comparés uniquement, de la similarité littérale, qui est la ressemblance de ces domaines à la fois en termes de propriétés de surface et de structure relationnelle. La comparaison entre des domaines ne partageant ni propriétés de surface, ni structure relationnelle, est appelée anomalie.

Nous continuons par la description des sous-processus psychologiques impliqués dans le raisonnement par analogie, faisant par ailleurs l'objet d'un large consensus dans la communauté scientifique (Gentner & Smith, 2012; Holyoak, 2012; Sternberg, 1977). Ceux-ci sont la récupération d'un domaine source, l'encodage des domaines, la mise en correspondance de ces domaines, l'inférence de nouvelles propriétés structurelles dans le domaine cible, et l'évaluation de la mise en correspondance. La récupération d'un domaine source intervient lorsque celui-ci n'est pas donné explicitement et consiste à invoquer un exemple en mémoire à long terme ayant une structure relationnelle similaire au domaine cible avec lequel on veut faire une analogie, et le faire passer en mémoire de travail. L'encodage est la construction d'une représentation des domaines source (s'il est donné) et cible en mémoire de travail afin d'effectuer les opérations suivantes. La mise en correspondance des domaines consiste à trouver les similarités en termes de rôles (pour les entités) et de relations dans les structures relationnelles comparées afin de maximiser la correspondance globale au niveau des relations de premier ordre et d'ordre plus haut. Le domaine cible étant souvent moins complet dans la représentation de sa structure relationnelle que le domaine source, le processus d'inférence utilise la mise en correspondance des deux domaines pour transférer des propriétés structurelles de la source vers la cible lorsque cette possibilité se présente. Enfin le processus d'évaluation de la mise en correspondance vérifie la cohérence globale et locale des correspondances entre les deux domaines et peut corriger cette mise en correspondance lorsqu'elle donne lieu à des aberrations logiques et peuvent mener à une re-représentation des domaines comparés sur la base de ces corrections. Cette théorie des différents processus impliqués dans le raisonnement par analogie vient de données expérimentales de Sternberg (Sternberg & Nigro, 1980; Sternberg & Rifkin, 1979; Sternberg, 1977) ayant montré que le modèle de régression attestant le mieux des données adultes était celui impliquant ces différents processus chez l'adulte. Cependant, chez l'enfant, la plus faible capacité de mémoire de travail limiterait la complétude des différents processus et la capacité des plus jeunes à trouver les correspondances entre la source et la cible.

La section suivante est dédiée aux différentes théories du raisonnement par analogie, et notamment du processus de mise en correspondance entre les domaines, qui est généralement considéré comme crucial dans ce type de raisonnement. Cette section s'attache aussi à décrire les implémentations informatiques de ces différentes théories. La première théorie décrite est la théorie de Gentner (Falkenhainer, Forbus, & Gentner, 1989; Gentner, 1983) de la mise en correspondance de structure (*Structure Mapping Theory*). Cette théorie décrit le processus de mise en correspondance dans ses détails, et est encore très influente. Elle établit notamment que différents principes contraignent les mises en correspondance possibles: les relations entre les objets doivent être conservées le plus possible durant la mise en correspondance des objets, les relations de plus haut niveau contraignent les mises en correspondance de relations de plus bas niveau, et les propriétés de surfaces tendent à être ignorées durant la mise en correspondance des objets. La théorie des contraintes multiples (*Multiconstraint Theory;* (Holyoak & Thagard, 1989) reprend en grande partie ces contraintes, auxquelles elle ajoute des contraintes pragmatiques: le but de la tâche pour laquelle est opérée la mise en correspondance influence son produit. Nous présentons également le modèle LISA (Hummel & Holyoak, 1997) qui intègre les contraintes liées à la capacité limitée de la mémoire de travail chez l'être humain, l'aspect dynamique et incrémentale de la mise en correspondance des domaines comparés, la sensibilité à certaines manières de présenter le problème, et certains aspects stratégiques, en plus des contraintes déjà prises en compte dans les anciens modèles. Deux modèles apparentés de par leur architecture et tentant d'expliquer la façon dont les représentations structurées émergent de l'interaction entre le matériel présenté et les concepts formés en mémoire à long terme, par une exploration en parallèle de différentes pistes et la stabilisation de la piste la plus prometteuse. La dernière théorie présentée est la théorie du *path-mapping* (Salvucci & Anderson, 2001). Celle-ci innove par rapport aux précédentes théories et aux modèles présentés jusque là par le fait que le processus de mise en correspondance des deux domaines est inséré dans une architecture utilisée pour la résolution de problème. Cette architecture comporte ainsi un système de gestion des buts de la tâche, qui au-delà d'influencer simplement les mises en correspondance de différents éléments, va produire des actions mesurables (pouvant mener ainsi à des prédictions quant à certains comportements fins tels que les mouvements oculaires) et terminer la tâche dès lors que le but principal est atteint. Cette théorie permet donc de générer des hypothèses quant aux différences entre les tâches de raisonnement par analogie, dont les buts ne sont pas équivalents en termes d'opérations de traitement de l'information.

Nous présentons également les trois principales théories du développement du raisonnement par analogie: la théorie de la transition relationnelle (*Relational Shift*), la théorie de la primauté relationnelle (*Relational Primacy*), et la théorie de la complexité relationnelle (*Relational Complexity*). La première établit que l'attention des enfants dans la comparaison de différents domaines va passer d'un focus sur les objets et leur similarité de surface à un focus plus orienté vers les relations entre les objets. La seconde s'oppose à la première par le fait qu'elle reconnait une attention de l'enfant envers les relations dès la naissance, mais explique l'apparition d'un raisonnement par analogie plus élaboré par un développement de la compréhension des contraintes qui pèsent sur ce type de raisonnement au niveau métacognitif. Ces deux théories mettent en avant le rôle du développement de la connaissance structurée du monde dans le développement de cette capacité. La théorie de la complexité relationnelle s'oppose aux deux autres par le fait qu'elle met l'accent sur les contraintes que posent les capacités de traitement de l'information en terme de mémoire de travail et des fonctions exécutives qui lui sont liées, tout en reconnaissant que la structuration du savoir de l'enfant peut dégager des ressources de traitement de l'information.

Après l'expositions des différentes théories sur le raisonnement par analogie, nous faisons la revue des différents facteurs affectant ce type de raisonnement, allant de facteurs perceptifs jusqu'à des facteurs stratégiques et métacognitifs, en passant par des facteurs liés à l'organisation du savoir et au langage, ainsi que des facteurs exécutifs, démontrant ainsi que le raisonnement par analogie est lié à l'interaction de modules cognitifs de bas comme de haut niveau. Parmi les facteurs perceptifs, les propriétés de surface du matériel utilisé pour présenter les domaines semble affecter le raisonnement analogique des enfants comme des adultes, notamment la concrétude de ce matériel, dans le sens de la quantité d'information que le matériel apporte. Les enfants sont également affectés par le fait que l'élément lié au but de la tâche se distingue des autres objets dans le domaine source. Un autre facteur perceptif, les similarités aussi bien relationnelle que de surface, affecte la capacité à faire des analogies quelque soit l'âge. La similarité de surface peut avoir un effet positif sur la mise en correspondance des éléments dans les deux domaines comparés, lorsqu'elle converge avec la mise en correspondance relationnelle, mais peut s'avérer nuisible lorsque ce n'est pas le cas. Néanmoins, malgré la difficulté à séparer ces deux aspects, des études montrent que ce n'est pas la similarité intrinsèque des domaines qui aurait un effet, mais la similarité entre les représentations de ces domaines par le sujet. La qualité de la représentation des domaines et de leur structure relationnelle parait d'ailleurs déterminante à plusieurs égards, et différentes manipulations ont tenté d'augmenter artificiellement cette qualité, par exemple la comparaison de différents exemples de la même structure relationnelle, ou des questionnaires ciblant cette structure. A un niveau plus intégré, de nombreux facteurs sémantiques apparaissent comme étant influents dans la capacité à raisonner par analogie: la distance sémantique entre les domaines comparés parait cruciale dans la capacité de remarquer l'analogie entre les structures et de transférer de l'information de l'une à l'autre. Egalement, l'organisation du système sémantique humain en différentes catégories semble guider la mise en correspondance des éléments des domaines. Un des effets les plus explorés dans l'influence que peut avoir le système sémantique humain sur le raisonnement par analogie est le rôle organisateur et attentionnel du langage dans la représentation des domaines, ainsi que la capacité à utiliser des mots en lieu de structure complète afin de réduire leur poids cognitif en mémoire de travail de ces structures. D'ailleurs, les limitations de la capacité en mémoire de travail, les différents systèmes qui la sous-tendent, ainsi que ses aspects exécutifs, ont également été étudiés dans le raisonnement par analogie, montrant son implication dans ce type de raisonnement et lui imposant des limites en termes de complexité des computations effectuées par l'être humain. Du point de vue du contrôle exécutif, cependant, la majorité des études se sont focalisées sur le rôle du contrôle inhibiteur, c'est-à-dire la capacité du sujet à empêcher certaines informations non pertinentes pour la tâche d'entrer en mémoire de travail. Les autres aspects exécutifs (la capacité à garder actif et mettre à jour le contenu de la mémoire de travail, et celle de changer de représentation du problème de manière active pour répondre de manière correcte à des variations dans la tâche) ont peu été étudiés dans le raisonnement par analogie. Un aspect lié à l'engagement des fonctions exécutives dans la résolution de problèmes est la capacité du sujet à maintenir des buts en mémoire de travail, et d'élaborer et de mettre en place une stratégie pour la résolution du problème rencontré. Ces aspects métacognitifs de planification mettent en jeu les fonctions exécutives qui vont permettre d'effectuer les opérations planifiées sur les représentations en mémoire de travail. Les aspects stratégiques ont beaucoup été étudiés dès le début de la recherche dans ce domaine, et ont mené à la découverte de l'utilisation de stratégies de construction de la réponse, surtout dans les cas plus simples, et d'élimination des mauvaises réponses dans le cas de problèmes plus complexes. Du point de vue du développement, les jeunes enfants semblent avoir du mal à prendre en compte toutes les contraintes nécessaires à l'élaboration d'une solution valide, et, dans un premier temps, se limiter à des réponses associées au domaine cible mais ne partageant pas, avec ce domaine, de relation similaire à la relation entretenue entre les éléments du domaine source. Cette difficulté des enfants à établir une stratégie correcte pour la solution des problèmes analogiques semble être liée au maintien du but des tâches de trouver une réponse qui entretienne la similarité de relation entre les domaines, ce qui est suggéré par une étude récente utilisant la technologie d'eye-tracking (Thibaut, French, Missault, Gérard, & Glady, 2011).

Le but principal de cette thèse est d'apporter, à travers notamment l'étude des stratégies visuelles employées dans les différentes tâches couramment utilisées pour tester le raisonnement par analogie, des connaissances sur les liens entre ces différents niveaux de fonctionnement cognitif. Certains de ces niveaux ont déjà été abordés mais dont la connaissance de leur implication dans le raisonnement par analogie reste lacunaires. En effet, de nombreuses données empiriques suggèrent que l'inhibition d'information non pertinente pour la tâche est impliquée dans le raisonnement normal et que des déficits dans ce module expliquent les difficultés de certaines populations de patients et des enfants avec les tâches de raisonnement par analogie. Cependant, la capacité d'inhibition de l'information est la fonction exécutive la plus étudiée dans ce raisonnement et nous ne savons quasiment rien de l'implication de la flexibilité cognitive (la capacité à changer de représentation de l'information pour s'adapter à la solution d'une tâche), ou du maintien et de la mise à jour de l'information en mémoire de travail. De même, les études sur l'implication des buts des tâches mais également de leur maintien et de leur oubli, une capacité connue pour se développer avec l'âge (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008a; Marcovitch, Boseovski, Knapp, & Kane, 2010), manquent dans la littérature sur le raisonnement par analogie. Ainsi le but principal de cette thèse est de comprendre comment les buts des tâches vont affecter les stratégies visuelles des adultes et enfants, et l'engagement de ressources exécutives, et de savoir si des différences en termes de maintien du but et de fonctions exécutives peuvent expliquer les différences, notamment en termes de stratégies visuelles, entre ces différents groupes d'âge.

II. Stratégies visuelles dans des problèmes analogiques sous forme de scènes

Le second chapitre présente des études sur la comparaison dans deux tâches de raisonnement par analogie: la tâche d'analogie formelle A:B::C:? et la tâche d'analogie entre scène. La première de ces tâches met clairement l'emphase sur la similarité entre les relations sans pointer particulièrement la nécessité de mettre en correspondance les éléments les composant, alors que la seconde, de part le fait que ses instructions établissent la nécessité de mettre en correspondance les éléments des deux domaines, pointe directement vers cette mise en correspondance. Ainsi nous nous attendions à ce que les différences entre l'emphase de ces tâches sur différents types d'information se répercutent sur les stratégies visuelles employées.

La première expérience de ce chapitre visait à étudier les différences développementales dans les stratégies visuelles dans la tâche d'analogies entre scènes, perspective qui n'avait encore jamais été étudiée. Nous avons répliqué la plupart des résultats obtenus dans une version papier et crayon de cette tâche par Richland, Morrison, & Holyoak (2006), à savoir que les enfants de 6-7 ans faisaient plus d'erreurs de type relationnel (le fait de choisir un élément impliqué dans la relation du domaine cible mais ne jouant pas le même rôle que l'élément pointé dans le domaine source), avaient des taux de réponses correctes moins bons et des temps de réaction supérieurs aux adultes. Cependant nous n'avons pas retrouvé le grand nombre d'erreurs dû au choix du distracteur ressemblant à l'objet pointé dans le domaine source. Cette différence est peut-être due à l'utilisation d'instructions ambigües quant au type de similarité à utiliser pour résoudre la tâche, instructions que nous avons clarifiées. Du point de vue de la recherche visuelle d'information, ce focus attentionnel sur la correspondance de rôle entre l'élément pointé dans l'image source et un des éléments de l'image cible, ainsi que cette absence d'effet des distracteurs perceptifs ont été retrouvés: les participants ont globalement plus regardés ces éléments que les autres, et très peu fixé le distracteur. Les saccades les plus fréquentes étaient effectuées entre les objets reliés par une relation à l'intérieur des domaines, ainsi qu'entre les éléments liés au but de la tâche (l'élément pointé et celui jouant le même rôle dans le domaine cible) uniquement dans le cas des adultes. Cette différence dans la quantité de saccades directement liées au but de la tâche, à savoir aligner les objets liés aux buts, correspondants en termes de rôles entre adultes et enfants, est cohérent avec notre explication de l'échec des enfants par l'impossibilité de maintenir ce but correctement tout au long de la tâche, et pourrait expliquer le plus grand nombre d'erreurs relationnelles de leur part. Les enfants ont également regardé proportionnellement plus longtemps que les adultes le distracteur, même si le taux de fixation était faible, ce qui suggère une plus grande difficulté à l'inhiber.

La seconde expérience présentée dans ce chapitre visait à comparer les stratégies visuelles des enfants de 6-7 ans et des adultes dans la tâche d'analogie entre scènes, et la tâche A:B::C:?. Cependant, pour minimiser les différences entre les deux tâches du point de vue de la présentation, cette dernière était présentée sous forme de scène, mais avec les instructions originelles (trouver quelque chose qui a la même relation avec l'élément pointé que celle qui existe entre les deux éléments de l'image source). Les différences entre adultes et enfant dans les erreurs relationnelles, les taux de réponses correctes et temps de réaction ont été retrouvés dans la tâche d'analogie de scène, et étaient également présentes dans la tâche A:B::C:? (mis à part les erreurs relationnelles qui n'étaient virtuellement pas possibles). Le distracteur relié à C dans cette tâche, par contre, a été souvent choisi comme réponse par les enfants. Du point de vue de la recherche d'information, les résultats précédents dans la tâche d'analogie de scène ont été répliqués. Dans la tâche A:B::C:?, les fixations étaient plus centrées sur C et la solution, et les enfants fixaient le distracteur de manière conséquente. Au niveau des saccades, celles impliquant des objets reliés à l'intérieur des domaines étaient également présentes. Cependant la tâche de type A:B::C:? n'a pas élicité de saccades inter-domaines, même chez les adultes. L'intérêt des enfants pour le distracteur c'est également montré par de plus nombreuses saccades entre celui-ci et C que chez les adultes. Ainsi les stratégies visuelles entre les deux tâches semblent avoir des caractéristiques communes dans la mise en place de stratégies pour leur résolution, à savoir le fort intérêt pour les relations entre les éléments dans les deux domaines. Cependant la tâche d'analogie de scène, du fait que sont but principal ciblait plus la mise en relation des éléments en termes de rôles dans les relations, élicite des saccades entre ces éléments, ce qui ne se retrouve pas dans la tâche A:B::C:?. Egalement le temps passé sur le distracteur était plus long dans la tâche A:B::C:? que dans la tâche d'analogie de scène. Ceci s'explique par le fait que l'accent, dans cette tâche, est mis sur la similarité entre les relations et que le distracteur en possède une avec C. Il est donc important de l'éliminer comme réponse potentielle.

La troisième expérience présentée dans ce chapitre, visait à comparer la tâche d'analogie de scène avec deux versions différentes de la tâche A:B::C:?, la version en contexte précédemment utilisée, et la version classique, avec les différents termes présentés dans des cadres séparés. En effet, la présentation sous forme de scène de l'information visuelle attire l'attention vers les relations entre les différents objets plutôt que vers les objets en eux-mêmes (Humphreys et al., 2010). Ainsi nous nous attendions à des différences à la fois en termes de taux de réponses correctes et de stratégies visuelles entre les deux versions de cette tâche. Les résultats comportementaux ont effectivement montré des différences de précision de réponse entre les deux versions de la tâche de type A:B::C:? chez les enfants, avec de meilleurs scores lorsque l'information est présentée sous forme de scène. Cette différence de score s'accompagnait d'une différence dans le nombre de saccades entre les éléments composant le domaine cible, suggérant une augmentation de l'attention portée à l'information relationnelle et à sa comparaison sous cette forme de présentation que dans la version classique. Dans l'ensemble, les mêmes patterns de fixations et de saccades, et les mêmes différences ont été retrouvés dans les deux tâches utilisées précédemment. Les différences entre la tâche de scène et celle de type A:B::C:? en contexte se retrouvent également entre la tâche de scènes et la tâche A:B::C:? classique. Ces données convergent avec celles de l'expérience précédente, et suggèrent que le but va moduler la stratégie utilisée dans la tâche de raisonnement par analogie. Egalement, elles suggèrent des différences perceptives liées à la présentation de l'information chez les enfants, avec une facilitation du traitement de l'information relationnelle lorsqu'elle est présentée sous forme de scène.

Ainsi les différentes études présentées dans ce chapitre montrent des résultats convergents quant aux stratégies visuelles employées dans les différentes tâches par les sujets. Les participants font beaucoup de saccades à l'intérieur des domaines afin d'encoder les relations entre les différents éléments les composant, mais au final font peut de mise en correspondance entre les domaines, sauf si le but de la tâche l'exige explicitement. Ces résultats sont en accord avec les prédictions du modèle de path-mapping: les sujets sont guidés par les buts de la tâche dans leur stratégie visuelle et effectuent la mise en correspondance entre les éléments liés au but de la tâche. Une fois que l'information nécessaire pour résoudre le problème a été récupérée, le sujet répond, sans mettre en correspondance de manière exhaustive les éléments des domaines comparés. Les différences entre enfants et adultes obtenues sont également compatibles avec le point de vue voulant que le raisonnement par analogie se développe en partie au moins grâce au développement du maintien du but et des fonctions exécutives. En effet, les enfants montrent moins de patterns de mouvements oculaires liés au but de la tâche d'analogie de scène, et cela en concordance avec des inversions de rôle plus fréquentes (c'est-à-dire des erreurs relationnelles). Ces études montrent également que la façon dont le matériel est présenté influence la capacité des enfants à résoudre des problèmes analogiques, notamment en guidant leur attention vers l'information importante pour résoudre les problèmes.

III. Stratégies visuelles des adultes dans des problèmes de types A:B::C:? complexes

Le troisième chapitre de la thèse présente deux expériences cherchant à tester la robustesse de la stratégie observée dans les problèmes de types A:B::C:? chez les adultes dans des problèmes imposant un coût cognitif plus conséquent. En effet, des différences ont été observées dans ce types de tâche avec la difficulté: les essais comportant un plus grand nombre de relations entre A et B provoquait le changement d'une stratégie de construction de la réponse vers une stratégie d'élimination des réponses non plausibles (Bethell-Fox, Lohman, & Snow, 1984). D'autres facteurs comme le type de distracteur affectent également la performance, notamment chez l'enfant. Il est donc possible qu'un distracteur évoquant de manière plus directe le but principal de la tâche (trouver un objet qui complète une relation similaire à celle observée entre A et B) affecte les stratégies visuelles des adultes.

La première expérience visait donc à savoir si un changement de stratégie tel que celui décrit par Bethell-Fox et al. (1984) était observé également lorsqu'un autre facteur que la charge en mémoire de travail était manipulé, à savoir une difficulté à se représenter la relation de manière suffisamment claire pour construire la réponse avant d'avoir vu les solutions possibles. Nous espérions que cette manipulation affecte l'engagement des fonctions exécutives telles que la flexibilité cognitive et l'inhibition. En effet, il est possible que les sujets dans les essais difficiles soient amenés à changer leur représentation de la relation entre

A et B face à la difficulté de trouver une solution correcte dans l'espace solution, et envisage plus les distracteurs, l'information provenant d'eux devant alors être inhibée pour se focaliser sur l'information correcte. Les résultats vont effectivement dans ce sens: le taux de fixation du distracteur est plus grand dans les essais plus difficiles que dans les essais faciles, tout comme le taux de saccades entre C et le distracteur. Les saccades entre C et la bonne réponse, et entre la solution et le distracteur étaient également moins fréquentes dans cette condition que dans la condition facile. Nous avons également divisé les essais en trois tranches afin d'appréhender la dynamique des stratégies visuelles dans ces différents essais. L'espace solution est déjà fixé lors de la première tranche des essais difficiles, et les participants effectuent déjà des saccades entre les différents mots de l'espace solution au début de ces essais, puis refont des saccades entre A et B durant la tranche médiane, et la dernière tranche, de ces essais. Ceci suggère effectivement une stratégie d'élimination de réponse, et que la paire AB est re-représentée face à l'information donnée dans l'espace solution. Les résultats vont également dans le sens d'une difficulté des participants à engager des ressources d'inhibition envers les distracteurs dans les essais plus complexes. Ainsi, cette étude suggère que la charge en mémoire de travail n'est pas le seul facteur rendant difficile la résolution de problèmes de type A:B::C:?. Le facteur de difficulté ici était un facteur général, mais l'observation du matériel suggère que l'imageabilité des relations différait entre les essais faciles et difficiles, et donc que la cette propriété module le raisonnement par analogie des adultes, ce qui est visible à travers leurs stratégies visuelles et l'engagement de ressources exécutives en réponse au matériel utilisé pour construire les analogies. Cette hypothèse concernant l'imageabilité devra cependant être testée de manière contrôlée par la suite.

La seconde expérience présentée dans ce chapitre est liée à l'étude des modulations des stratégies des adultes par le but de la tâche en cours. En effet, nous avons manipulé le type de distracteur pour qu'il soit plus ou moins lié au but principal de la tâche: la moitié des essais comportait des distracteurs reliés à C par n'importe qu'elle relation sémantique, ce type de distracteur étant peu attractif car ne répondant pas au but de similarité de relation entre les deux paires comparées dans les problèmes de type A:B::C:?; l'autre moitié des essais comportait des distracteurs reliés à C de la même manière que B à A, mais dans une correspondance croisée, c'est-à-dire que les rôles de C et de la solution étaient inversés. Nous avons fait l'hypothèse que ce type de distracteur serait beaucoup plus attractif du fait de leur lien direct avec le but de la tâche. Les résultats comportementaux suggèrent effectivement que ce type de distracteur est plus attractif: les participants ont choisi ce type de distracteur plus souvent que les distracteurs simplement liés à C, ce qui a causé des scores moins bons dans la première condition que dans la seconde. Cette sélection accrue s'est accompagnée de variation dans la recherche d'information visuelle par les participants: les participants ont regardé la solution moins longtemps et le distracteur plus longtemps en proportion dans les essais avec distracteur relié à C de manière opposée que dans les autres essais. Ils ont également fait moins de comparaisons entre les différentes solutions possibles dans la première condition que dans la seconde. Enfin les temps de réactions étaient plus brefs avec les distracteurs reliés de manière opposée qu'avec les distracteurs simplement reliés à C. Ces différents résultats suggèrent que l'information procurée par le distracteur relié de manière opposée, du fait de son lien avec les buts de la tâche, a été un puissant attracteur dans le raisonnement des participants, les poussant à peu ou ne pas engager leur inhibition envers cette information, et à passer outre le processus d'évaluation de la mise en correspondance des éléments des deux domaines.

Pris dans l'ensemble, les résultats de ces deux expériences confirment les rôles des saccades entre A et B, et C et les solutions possibles dans les problèmes de type A:B::C:?en lien avec l'encodage des relations entre ces différents termes. Elles confirment également l'absence de saccades liées à la mise en correspondance des éléments des différents domaines, ceci en lien avec le but de la tâche qui n'est pas de les mettre en correspondance, mais de mettre en correspondance les relations entre ces éléments et de les comparer. Ce focus sur la similarité relationnelle en elle-même, indépendamment des éléments qui les composent est également suggéré par la puissance du distracteur relié à C de manière opposée qui ne devrait pas être choisi si cette mise en correspondance entre éléments était faite spontanément dans cette tâche. Ces études confirment également l'engagement différentiel des fonctions exécutives en lien avec les contraintes de la tâche et ses buts.

IV. Une nouvelle méthode pour classer des trajectoires visuelles

Le quatrième chapitre est consacré à la description et l'utilisation d'un nouvel algorithme de tri de trajectoires visuelles afin de savoir si des groupes diffèrent réellement dans ces trajectoires. Cet algorithme, basé sur la méthode d'analyse des scanpaths de Jarodzka et al. (2010) alliée à une technique de positionnement multidimensionnel (Multidimensional Scaling) permettant la cartographie des différents individus en se basant sur les différences entre leurs trajectoires visuelles respectives, et à un réseau de neurone (perceptron multicouche) permettant la classification des points sur la carte, est utilisé afin de distinguer si les trajectoires visuelles des enfants et des adultes dans les trois tâches présentées dans la troisième expérience du second chapitre de ce manuscrit diffèrent réellement. Ce qui distingue la méthode d'analyse de Jarodzka et al. (2010) des autres méthodes d'analyse de données oculomotrices est sa capacité à tenir compte de la structure même des trajectoires visuelles alors que les autres moyens d'analyses tendent à ne pas tenir compte de cette information pourtant cruciale. Un second intérêt de cette méthode est la possibilité de comparaison de trajectoires visuelles de durées différentes, ce qui s'avère utile dans l'étude de données développementales dans lesquelles les temps de réactions moyens diffèrent.

L'algorithme commence donc par trouver une valeur de différence entre toutes les paires de trajectoires visuelles entre les enfants, entre les adultes, et entre enfants et adultes. Pour cela, chaque trajectoire est transformée de sa forme initiale (liste de cordonnées) en une suite de vecteurs. Chaque liste de vecteurs est alors réduite par addition des vecteurs consécutifs dont l'amplitude est en dessous du seuil choisi ou si deux de ces vecteurs consécutifs forment un angle approximativement droit. Une fois cette étape de simplification, chaque vecteur d'une liste (constituant une trajectoire visuelle pendant un essai) est comparé à chaque vecteur d'une seconde liste (constituant une seconde trajectoire visuelle) sur la base d'un critère (par exemple leur longueur) pour donner une matrice rectangulaire contenant chaque valeurs de différence entre chaque combinaison de deux vecteurs issue de ces deux listes. Le chemin dans cette matrice minimisant la somme totale des différences entre paires de vecteurs est trouvé, partant de la comparaison des deux premiers vecteurs et allant jusqu'à la comparaison des deux derniers vecteurs, est trouvé itérativement, en autorisant uniquement les déplacements dans cette matrice entre des cellules contenant des comparaisons de vecteurs adjacents à ceux utilisés dans la comparaison de l'itération précédente. La somme des différences se situant sur ce chemin de moindre différence est alors la valeur de la différence entre les deux trajectoires visuelles comparées.

Une fois comparées deux à deux toutes les trajectoires de tous les participants dans des essais identiques, la moyenne des différences entre ces individus est calculée, et les participants sont positionnés sur une carte ou la distance entre deux individus reflète la différence moyenne entre ces deux participants. Les coordonnées de ces points sont utilisées pour entrainer et tester un réseau de neurones multicouche, en utilisant une technique validation croisée de Leave-One-Out (avec un échantillon de n sujets, n-1 sujets sont utilisés pour entrainer le réseau est la classification du dernier sujet par le réseau est testée; tous les sujets sont testés alternativement au cours de n procédures d'entrainement et de test).

Les résultats obtenus montrent effectivement que les enfants et les adultes sont classé par le réseau de manière non aléatoire dans leurs groupes respectifs dans les trois tâches (tâches d'analogie entre scènes, tâches A:B::C:? avec et sans contexte). Ainsi cette technique permet de répondre de manière quantitative à la question de la différence des stratégies visuelles entre enfants et adultes de manière positive.

V. Implication de la flexibilité cognitive dans le raisonnement par analogie des enfants

Le cinquième chapitre est quant à lui consacré à des expériences tentant de démontrer l'implication de la flexibilité cognitive, une des fonctions exécutives fréquemment citées, dans le raisonnement par analogie à travers ses limitations chez l'enfant. En effet, les enfants en âge préscolaire réussissent mal certaines tâches nécessitant de changer de représentation durant leur solution. Ainsi, si le raisonnement analogique nécessite dans certains cas de faire appel à la flexibilité cognitive, ces enfants devraient avoir des difficultés à parvenir à résoudre des tâches de raisonnement par analogie.

La première des expériences présentées dans ce chapitre utilise une tâche de type A:B::C:? modifiée afin d'induire un représentation de la paire AB, A et B étant possiblement liés par deux relations différentes (une seule étant utilisée pour construire la pair C:solution) en utilisant deux paires d'images avant la présentation du problème en lui-même. Ces deux paires pouvaient être reliées soit par la relation identique à celle utilisée pour construire le problème (condition de facilitation) ou bien par une relation différente (condition de re-représentation), la seconde étant celle demandant d'engager de la flexibilité cognitive. Ces deux conditions étaient comparées à une troisième, contrôle, ne présentant que deux paires de cadres vides à la place des paires d'images. Avec cette tâche, nous avons testé des enfants de 5-6 ans et de 7-8 ans. Les résultats de cette tâche sont mitigés: nous n'avons pas trouvé d'effet de la condition, ni d'interaction de ce facteur avec l'âge sur les scores, ni sur les temps de réaction. Le seul indice d'un effet de la présentation de paires avant le problème est une diminution du temps de réaction chez les participants plus âgés, dans la condition de facilitation. Cette absence d'effet peut s'expliquer de différentes manières: la tâche en elle-même était peut-être trop complexe pour de jeunes enfants dans sa structure, et ceux-ci n'ont peut-être pas compris le bénéfice de prêter attention à l'information relationnelle de ces deux paires, étant donné que les essais d'entraînement étaient peu nombreux et montraient chaque condition une seule fois. Ainsi, un seul essai d'entrainement montrait une information pertinente venant des paires d'images précédent le problème.

La seconde expérience de ce chapitre visait à créer une procédure facilitant l'intégration de la paire AB, basée sur les résultats de Thibaut et al. (2011) montrant que les enfants ont du mal à maintenir le but de similarité des relations entre A et B, et C et la solution, et qu'ils prêtent peu attention à la relation entre A et B. Afin de faciliter le maintien du but chez les enfants préscolaires, nous avons modifié la procédure habituelle de la tâche A:B::C:?: la paire AB était présentée en premier et l'enfant devait dénommer la relation entre A et B, avant qu'on lui présente le reste du problème et qu'il puisse tenter de le résoudre. Cette procédure a été testée avec des enfants de 5-6 ans, en comparaison de la procédure standard. Nos résultats montrent qu'en effet, les scores sont meilleurs lorsque l'enfant doit nommer la relation liant la paire AB qu'il voit avant le reste du problème, que lorsqu'il ne doit pas le faire et voit le problème entier dès le départ. Cette procédure est encore une fois une démonstration de la difficulté qu'ont les enfants à maintenir le but de la tâche tout au long de la résolution du problème. Ainsi, augmenter le focus attentionnel des enfants sur la paire AB et la relation entretenue par ses éléments l'un avec l'autre facilite le maintien de ce but.

La dernière expérience présentée dans ce chapitre utilise ce résultat de la procédure dans laquelle les enfants voient la paire AB avant le reste du problème et verbalise la relation entre ses éléments pour étudier le lien entre flexibilité cognitive et raisonnement par analogie. Ainsi nous avons utilisé des essais différents dans cette tâche: certains essais devaient être résolus simplement en utilisant la relation d'identité de couleur entre A et B, pour trouver une solution qui partageait sa couleur avec C. Un autre type d'essai étaient basés sur la relation sémantique entre les images représentées en A et B, ces images ne partageant pas leur couleur, et se résolvaient en trouvant une image qui partageait la même relation sémantique avec C. Le troisième type d'essai, crucial pour l'étude de la flexibilité, était constitué de paires AB à la fois liées par l'identité de couleur de ses éléments et par une relation sémantique, mais ne pouvait se résoudre que par la relation sémantique, aucun objet dans l'espace solution n'ayant la même couleur que C. Ainsi, si les enfants interprètent la paire sur la dimension couleur avant de voir le reste du problème, ils devront faire preuve de flexibilité cognitive pour trouver l'autre représentation nécessaire à la solution de ces essais. Les résultats vont effectivement dans le sens d'une difficulté à changer de représentation durant les essais nécessitant ce changement: les scores étaient plus faibles, dans la condition ambigüe quant à la représentation à adopter pour la paire AB, lorsque les enfants utilisaient l'identité de couleur que dans les conditions non ambigües. Cependant l'analyse des scores dans les essais dans lesquels les enfants ont trouvé directement la relation sémantique entre A et B ne montre aucune différence significative avec les essais non ambigus sémantiques. Ces résultats suggèrent que l'interprétation initialement incorrecte de la paire AB a été difficile à surmonter pour les enfants qui ont alors été incapables de résoudre correctement les problèmes analogiques.

Les résultats de ces études sont compatibles avec la vision du développement du raisonnement par analogie comme dépendant au moins partiellement de celui de la capacité à maintenir le but et des fonctions exécutives. Cependant ces études laissent la question du déficit d'engagement des fonctions exécutives due à un déficit de maintien du but, ou bien d'un déficit dans la capacité de flexibilité cognitive de ces enfants en elle-même. Cependant ces études sont une illustration du coût cognitif lié à la re-représentation du matériel.

VI. Discussion générale

Le cinquième et dernier chapitre de cette thèse s'intéresse à la discussion des résultats que nous avons obtenus dans les différentes expériences présentées dans cette thèse par rapport au cadre théorique et la problématique élaborés durant l'introduction et notamment les modèles présentés et la littérature utilisant l'eye-tracking pour étudier le raisonnement par analogie. Il présente également les perspectives qu'ouvre le travail de recherche décrit.

Les résultats que nous avons obtenus sont consistants avec d’autres données obtenues dans la tâche d’analogie de scène par Gordon & Moser (2007), et dans la tâche de type A:B::C:? par Bethell-Fox et al. (1984). La première de ces études montre effectivement une majorité de saccades entre les éléments d’un même domaine, des fixations plus importantes sur les éléments impliqués dans une relation, et peu de fixation des distracteurs. Nos résultats chez l’adulte sont cohérents avec ces données mais ajoutent à cette connaissance préalable l’information des saccades inter-domaines, notamment celle liée au but de la tâche: les participants dans cette tâche d’analogie de scène aligne visuellement les éléments liés au but dans le domaine source (l’élément pointé) et dans le domaine cible (celui qui partage le même rôle que ce dernier), montrant une influence du but de la tâche sur la stratégie employée, et donc certainement sur les processus mis en jeu durant la tâche.

La seconde étude est moins directement comparable à la notre étant donné que nous avons utilisé un type d'analyse différent de celui de Bethell-Fox et al. (1984), mais reste cohérente avec les données que nous avons obtenues. En effet, en faisant varier la complexité relationnelle des essais, ces auteurs ont observé de plus nombreux retours sur la paire AB dans les essais complexes que dans les essais simples et l'emploi d'une stratégie d'élimination de la réponse, alors qu'une stratégie de construction de la réponse était employée dans les essais plus simples. Nos études, en plus de révéler le même type de stratégies et de retour sur AB dans les essais complexes, suggèrent également que les participants n'alignent pas directement les deux domaines, mais se contentent de comparer la similarité de la relation, étant donné que les instructions de la tâche mettent l'accent sur ce point. Ceci est cohérent avec le fait qu'un distracteur qui partage, avec C, la similarité de relation avec la paire AB, mais dont la mise en correspondance en terme de rôle est inversée par rapport à AB, provoque un grand nombre d'erreurs chez les adultes, et diminuent le nombre de comparaison dans l'espace solution. Ainsi le but principal de la tâche étant atteint, la tâche se termine sans l'opération d'évaluation de la mise en correspondance des deux domaines.

Ainsi, dans les différentes tâches de raisonnement par analogies proposées à nos participants, nous avons trouvé des composantes communes: l'encodage des relations se fait de la même manière, et l'attention portée aux distracteurs directement liés au but principal de la tâche est plus grande que sur des distracteurs peu liés au but. Egalement, dans ces deux tâches, on observe peu de saccades liées à la mise en relation directe des éléments des deux domaines, mise à part les mises en correspondances directement liées au but principal de la tâche. La principale différence entre ces deux tâches est, elle aussi, liée aux buts distincts de ces deux tâches: la présence de saccades entre les éléments correspondants en terme de rôles dans les relations n'est présente que dans la tâche d'analogies entre scènes dont les instructions demande explicitement cette mise en correspondance.

Les effets du but sur la tâche ont été pris en compte par deux modèles: ACME (Holyoak & Thagard, 1989) et le modèle de path-mapping (Salvucci & Anderson, 2001). Le premier cependant est limité dans ses prédictions du fait que ce n'est qu'un modèle du processus de mise en correspondance et ne dit rien sur l'encodage ou l'évaluation de la mise en correspondance. Ce modèle est néanmoins critiquable du fait qu'il atteint systématiquement une mise en correspondance totale entre les deux domaines, ce que nos données ne semble pas confirmer. Au contraire elles supportent plus les prédictions du modèle de path-mapping qui veut que, lorsque l'information et les comparaisons nécessaires à la résolution du but principal de la tâche ont été effectuées, la réponse est donnée. Egalement, le fait que les participants continuent à explorer le matériel tout au long de la tâche, et que les sujets reviennent sur le domaine source après avoir exploré le domaine cible dans certains cas d'essais complexes, suggère que la représentation des domaines comparés est influencée par les processus de mise en correspondance, de transfert et d'évaluation, comme le suggère les modèles Copycat et Tabletop (French, 1995; Mitchell, 1993).

Du point de vue développemental, plusieurs de nos données suggèrent que les enfants ont des difficultés à maintenir le but de la tâche au cours de sa résolution. En effet, les enfants, dans la tâche d'analogie de scène, font moins de saccades entre les éléments liés par leur communauté de rôle dans les domaines source et cibles, et parallèlement font plus d'erreurs de type relationnelles, c'est-à-dire d'erreur de rôle dans la relation cible. Egalement, de manière cohérente avec les résultats de Thibaut et al. (2011) qui montraient que les enfants regardaient moins le domaine source, en proportion, comparés aux adultes, nos résultats montrent qu'en aidant les enfants à se focaliser sur AB par une procédure montrant cette paire avant le reste du problème, et leur demandant de verbaliser la relation entre ces images, ceux-ci réussissent mieux dans cette tâche.

Les théories du développement du raisonnement par analogie (c'est-à-dire les théories de transition relationnelle, de primauté relationnelle et de la complexité relationnelle) laissent la place à de tels facteurs métacognitifs, mais seulement de manière vague. Ces données sont un argument pour la prise en compte explicite du développement du maintien du but dans ces théories. Egalement, les modèles de raisonnement par analogie, et notamment celui-de path-mapping, pourraient être adaptés pour tenir compte de la difficulté des enfants à maintenir le but de la tâche. Ainsi le modèle de path-mapping, en intégrant la structure de buts de la tâche dans les objets retenus en mémoire de travail, et donc en laissant la possibilité que cette structure ne soit pas rappelée correctement, pourrait modéliser ce genre de données. Ce modèle prédirait une compétition en mémoire de travail de la structure de buts de la tâche et de la complexité relationnelle des structures des domaines comparés.

Les données que nous avons recueillies sont également discutées en termes de fonctions exécutives, et de leur interaction avec d'une part la représentation des buts de la tâche, et d'autre part les représentations des domaines comparés. En effet, les fonctions exécutives sont à l'interface de ces deux types de représentations; elles permettent de manipuler l'information des représentations des domaines en vue de la transformer pour atteindre les buts posés par la tâche. Un des arguments en faveur de cette vision des fonctions exécutives est le fait que les distracteurs sont plus difficilement inhibés dans les cas où le distracteur prend en compte la plupart des contraintes qui reposaient sur la solution de la tâche (c'est-à-dire la similarité de sa relation avec C avec celle de la paire AB). Egalement, lorsque la représentation du domaine source n'était pas assez contraignante (c'est-à-dire représentée de manière suffisamment claire pour discriminer la solution des autres réponses possibles reliées à C) provoquait une difficulté pour les adultes à engager l'inhibition de l'information provenant des distracteurs. Cette difficulté d'inhibition s'est retrouvée dans les patterns visuels des participants, avec de plus grandes fixations sur le distracteurs reliés à C, et de plus nombreuses saccades entre ceux-ci et C.

Ces résultats correspondent bien avec les points de vue actuels sur les fonctions exécutives montrant leur lien d'une part avec leur substrat (Chevalier, 2010) et leur lien avec la représentation et le maintien du but (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008b). Ils sont également consistent avec les modèles mettant l'inhibition de l'information en mémoire de travail au centre de leur fonctionnement. C'est le cas de LISA (Hummel & Holyoak, 1997), dont la construction d'une représentation en mémoire de travail est liée à sa capacité à inhiber et à coordonner les activations de certaines informations en mémoire de travail dans le temps. Cependant, ce modèle souffre des mêmes problèmes qu'ACME déjà relevés plus haut, à savoir le fait qu'il fasse une mise en correspondance globale des deux domaines, et que ses représentations soient pré-programmées par les expérimentateurs, ne laissant ainsi pas la place à des représentations peux claires d'influencer l'engagement de l'inhibition. Egalement, il serait difficile de le faire évoluer vers la prise en compte de buts spécifiques à différentes tâches de raisonnement par analogie et de faire des prédictions spécifiques à partir de ce modèle par rapport à des données de mouvement oculaires, celui-ci se limitant à la modélisation de la mise en correspondance et ne s'intéressant pas à l'encodage, ni aux autres processus du raisonnement par analogie.

L'engagement du contrôle exécutif dans le raisonnement par analogie est également suggéré par les données obtenues chez l'enfant. En règle générale, ils sont plus susceptibles de choisir des distracteurs reliés à C que les adultes, les regardent plus longtemps et font plus de saccades entre eux et les éléments qui leur étaient reliés. Ceci suggère une difficulté à engager leur inhibition sur ces objets. Egalement, les enfants, lorsqu'ils sont ancrés dans une première représentation de la relation source qui n'était pas utile pour la résolution des problèmes par analogie, font plus d'erreurs que si leur représentation initiale se porte sur la relation correcte. Ceci suggère une incapacité à engager leur flexibilité cognitive pour re-représenter le domaine source et résoudre le problème. Ainsi, une des possibilités que les données de cette dissertation font entrevoir est que le maintien du but, difficile chez l'enfant, va les empêcher de mettre en place des ressources exécutives lorsque c'est nécessaire.

Le manuscrit termine sur les perspectives que les données collectées dans les différents chapitres font entrevoir. Ainsi, à très court terme, il serait intéressant de contrôler plus avant les différences de matériel entre les tâche d'analogie de scène et A:B::C:? en contexte, car les matériels que nous avons utilisés, développés par différentes équipes, ne donnent pas la même information sur les relations représentées. En effet, les analogies de scène sont plus explicites dans les interactions entre les éléments composant les scènes que le matériel que nous avons créé pour la tâche de type A:B::C:?. Ainsi un contrôle serait d'utiliser le matériel de la tâche A:B::C:? en contexte dans la tâche de scène, en faisant varier simplement l'objet vers lequel la flèche pointe, et les instructions.

A moyen terme, il serait également intéressant d'étudier l'interaction prédite entre les charges en mémoire de travail qu'exercent les représentations respectivement des buts de la tâche et des domaines comparés, ainsi que de faire varier l'activation du but par l'entremise d'essais où la solution est rendue évidente par une similarité de surface soulignant les correspondances en terme de rôles, et d'observer à quel point cette extinction du but affecterait les performances chez l'adulte et l'enfant. Egalement il serait intéressant de dissocier l'incapacité à être flexible dans le raisonnement par analogie à cause d'une immaturité de cette fonction exécutive, d'une incapacité due à une difficulté à engager cette fonction liée à la négligence de but. Ces deux points de vue font des prédictions différentes au niveau des données eye-tracking qui seraient obtenues dans notre tâche testant l'implication de la flexibilité cognitive dans le raisonnement par analogie chez l'enfant.

A plus long terme, il serait également intéressant d'étudier chez l'adulte les différences d'engagement des fonctions exécutives dues aux propriétés sémantiques des domaines comparés impactant les représentations de ces domaines que se forment les participants. Nous avons vu qu'un de ces facteurs était peut-être l'imageabilité des concepts relationnels utilisés pour construire les problèmes. Cependant, ce facteur n'a pas été testé directement dans notre étude. D'autres facteurs sémantiques pourraient également affecter l'engagement de ressources exécutives, tels que des aspects thématiques ou catégoriels. Un autre aspect à développer serait la modélisation des effets d'interaction entre maintien du but, d'engagement des fonctions exécutives, et de formation de représentation, ces trois facteurs n'ayant jamais été pris en compte simultanément dans un modèle, en se basant sur les points forts des modèles simulant ces différents facteurs de manière isolée.

Introduction

Chapter I: Theoretical introduction

I. Definition of analogy-making

Finding similarities between objects, movements or situations is one of the most common mental processes of human cognition. Indeed, it is so closely intertwined with human thought and knowledge. Much of what our brain does involve finding regularities and continuity in the world: the ability of finding things similar is part and parcel of everyday thinking to the extent it overshadows the constant changes in our environment. In fact, analogical perception is so central to our conceptual system that it has been called the "core of human cognition" (Hofstadter, 2001).

The exact definition of analogy-making has been debated by cognitive scientists for decades, some of them arguing that every act of finding things similar is an analogy (French, 1995; Hofstadter, 2001; Mitchell, 1993), others constraining the domain of analogy-making to a subset of similarity processes (Gentner, 1983; Holyoak & Thagard, 1989). In this dissertation, we will adopt the more constrained view which defines analogy-making as the ability to compare and find similarities between two domains on the basis of the relations between the elements composing the two domains. Hence, we will not consider finding "mere" featural similarities between these elements to be analogical reasoning. In fact, in many cases it is precisely these featural similarities that have to be ignored in order to draw meaningful analogies. The domain whose representation is most complete (from the perspective of the person making an analogy) is often called *source* or *base* domain, while the other domain whose representation has to be completed is referred to as the *target* domain. Thus, drawing an analogy essentially involves comparing and transferring relational information from the source to the target domain.

Defined in this way, analogy lies somewhere on the continuum of similarity perceptions and judgments that contains cognitive processes, such as recognition, generalization, the ability to map perceptual inputs onto already formed concepts, and categorization (French, 1995). "Recognition," according to these authors, requires the least "slippage," and, as such, lies at one end of the continuum, whereas "analogy-making" is thought to be the similarity process that requires the most control and conceptual slippage, and therefore lies at the other end of the continuum. We agree with French (1995) that analogy-making requires a greater degree of conceptual slippage than recognition and categorization. However the degree of slippage is a multidimensional concept, as expressed in Barnett & Ceci's (2002) taxonomy in which distance between two domains depends on their respective contents and their associated physical, temporal, functional, and social contexts. In addition, the perception of this distance might also change during development.

Another taxonomy of analogy-making has been made by Gentner (1989), who pits “mere appearance similarity” against “structural similarity”, the latter being the stuff of true analogies. In Gentner's view, similarity is two dimensional: similarity of features and similarity of relations. Mere appearance similarity is considered to be when only surface (i.e., feature) similarity exists between the two domains compared. For example, the words "dog" and "god" constitute a case of mere appearance similarity matching. Literal similarity is the case when surface similarity and relational similarity both contribute to the similarity of the two domains compared. An example of a literal similarity match would be one between two atoms, say, a carbon and an oxygen atom. Both are made up of electrons, neutrons and protons, and the organization between these entities is the same, i.e., the electrons revolve around a nucleus which consists of neutrons and protons. Analogies, on the other hand, involve the comparison of two domains on the sole basis of their *relational* structure. Comparisons between domains sharing neither surface, nor relational similarity are called anomalies.

Analogy-making should also be distinguished from metaphor comprehension and processing (Billow, 1977), which are often related to true analogies, for example, in Gentner's (1989) taxonomy, in which metaphors occupy considerable space in a two dimensional environment that includes true analogies, mere appearances matches, as well as anomalies. Holyoak (2012) relates metaphors to analogies, because both are designed to convey information from a source domain in order to induce a representation in a target domain so that the two domains can be mapped onto each other. However, Holyoak argues that metaphors are a special kind of analogy, since the two domains compared are always distant, often mixed together, rather than simply compared, and that metaphors often involve other conceptual blendings, such as metonymy.

To sum up, we have argued that similarity detection and processing are central to our mind's behavior, and that similarity processing can be decomposed into different processes, among them: recognition, generalization, categorization, and analogy-making.

II. The sub-processes of analogy-making

There is broad agreement on the sub-processes involved in analogical reasoning in the scientific literature. It is generally accepted that analogical reasoning can be divided into the retrieval of a source (if the source is not given explicitly), or the encoding of the source domain (if it is explicitly given), the mapping of the source onto the target domain, the evaluation of the mapping and potential inferences between the domains, and the transfer and inferences that are made in the target on the basis of what is known about the source (Gentner & Forbus, 2011; Gentner & Smith, 2012; Holyoak, 2012; Sternberg, 1977). Usually, mapping is considered to be the most crucial process (Gentner & Smith, 2012). These different sub-processes were found to differentially modulate several brain areas' activation (Krawczyk, McClelland, Donovan, Tillman, & Maguire, 2010; Maguire, McClelland, Donovan, Tillman, & Krawczyk, 2012; Qiu, Li, Chen, & Zhang, 2008). Moreover, these sub-processes are subject to more general cognitive constraints, such as working memory capacity and executive functions.

II. a. Retrieval/encoding of the source

The retrieval of a source domain is the sub-process of finding a domain in long term memory that has the same relational structure as the domain that is currently under consideration (i.e., the target domain) in order to draw an analogy. This happens when the source domain is not already explicitly given by the problem (this often occurs in so-called "explanatory analogies" in which we try to explain a novel situation by finding an analogy with another, better-known or more easily understood situation: "That's like..."). By doing so, one activates a representation of the relational structure of a domain that has been previously stored in long term memory. This representation is kept active in working memory and the subsequent operations involving the analogy are carried out. An example of this process would be an elementary school teacher trying to teach her class fractions using an analogy with a domain with which the children are more familiar. Trying to explain "fractions," the teacher might try to retrieve a source analogue from memory, and find a familiar situation in which units are cut into smaller slices. She might retrieve a situation involving cutting a pizza into slices, for examples, which would activate a representation of the relational structure of "cutting pizza into slices" in working memory.

The encoding of the source is the counterpart of the retrieval sub-process when one is explicitly given the source domain. In this case, the source domain is translated into an internal representation of its relational structure and its objects and object features, and is kept active in working memory. In contrast to the situation where the teacher had to discover her own source domain (i.e., cutting pizzas into slices), in the teacher's manual, fractions are described in terms of cutting a segment in different sub-segments. In this case, this description is encoded and maintained in working memory to permit the next sub-processes.

In the above examples, in one case, the teacher relied on memory search and retrieval to unearth an analogy (cutting a pizza into slices) to explain fractions to her pupils, and, in the second case, she encoded an explicit source domain (cutting a line segment into sections) provided by her teacher's manual. Both resulted in the activation of a structured representation of an analog in our teacher's working memory.

II. b. Mapping

The mapping phase of analogical reasoning is the phase in which the base and target domains are put into correspondence. During mapping, relations in the two domains are compared and aligned in order to find possible matches between the two domains' elements and relations.

Let us return to our example of cutting pizza slices and fractions. During the mapping sub-process, our teacher would put into correspondence the following elements and relations: the number of pizzas cut plays the same role as the number of units, the number of slices into which each pizza is cut corresponds to the denominator, and the number of slices picked by someone corresponds to the numerator. The relations between these different elements are also matched: the division of the fraction's numerator by its denominator corresponds to the amount of a pizza eaten, i.e., the number of slices taken with respect to how many slices make up a pizza.

The key idea is that mapping causes an alignment, however imperfect, between the two domains that are compared.

II. c. Transfer and inferences

When the two domains are aligned, even partially, inferences in the target domain can be drawn using the knowledge from the source domain. This sub-process is usually called transfer or analogical inference. To illustrate the sub-process of inference, we can draw on the above analogy between pizza slices and fractions. A clever student might use this analogy between pizzas and fractions to derive the conclusion that to add fractions, they must be expressed with the same denominator, since only slices of the same size can be added conveniently to make an entire pizza. This is a case of analogical inference, as this student has used his knowledge about pizza slices and whole pizzas to predict functioning in the fraction domain.

Analogical inference thus can be seen as a generalization of a relational sub-structure of one domain to the other on the basis of their mutual correspondences.

II. d. Evaluation

Evaluation is the sub-process that is used to control mapping and inferences. Mapping and inferences are evaluated on the basis, not only of their correspondence to facts about the world, but also on the basis of the goals of the analogical task, the adaptability of the source in order to draw an inference in the target, and the value of the knowledge derived from the source in the target (Gentner & Smith, 2012). The evaluation sub-process might also be involved in the control of potential errors in the mapping sub-process, and of the omission of some information or the justification of inference under low evidence (Sternberg, 1977).

To illustrate the evaluation process, imagine that, while elaborating her analogy between pizzas and fractions, our professor might have wondered if pizzas were appropriate to convey correct analogical inferences, due to the difficulty of cutting slices of exactly the same size. As a result she might have replaced them with the more abstract example of lines and segments of lines, given in her teacher's manual.

The clever student might have asked his teacher about how to add fractions, in order to justify his inference, his current knowledge not allowing himself to justify it by himself. A poorer student might have first mapped the total number of pizzas to the numerator, but corrected the mapping when faced with the contradictory evidence and incoherent descriptions that this choice led to. This leads to what Gentner calls re-representation (i.e., the modification of the representation of at least one of the two domains, based on the mapping between the two domains, to augment the match between them; Gentner & Kurtz, 2006) These examples illustrate the evaluation of the mapping and inferences sub-processes during analogical reasoning.

The evaluation of an analogy is intrinsically dependent on the subjective goals that are pursued by the subject, and, thus, it necessarily varies according to the context of the analogical task.

II. e. Conclusion

The different sub-processes of analogical reasoning presented above are well-acknowledged by the research community. We have tried to illustrate them by means of an example, showing that they arise naturally when a comparison of different domains occurs in everyday life. Different theories of analogy making account for these processes, especially the mapping process, in different ways. Little consensus has been reached concerning the cognitive computations involved in these operations. The next section is an attempt to present the main theories of adult analogical reasoning and to summarize the differences between various theories of analogy making in terms of these sub-processes.

III. Theories of analogical reasoning

The following section first discusses the necessity of the sub-processes presented in the former section, and then describes the principal theories about analogical reasoning. It ends with comparisons of the different theories in terms of the postulated cognitive processes, psychological limitations, and order of information processing by subjects.

III.a. Necessity of the sub-processes

The necessity of the sub-processes presented in section II was highly debated in early research on analogical reasoning, and several proposals were made, including or not the totality of these sub-processes. One of these early scientific explorations of the sub-processes of analogical reasoning was done by Sternberg (1977). He proposed a theory of analogical reasoning in A:B::C:? problems including the sub-processes of encoding, inference (of the relations between objects constituting the problems), mapping, application of the inference to the C term (what we called transfer or inference above) along with justification which was considered optional. He tested his model of sub-processes against other models excluding mapping (Johnson, 1962; Shalom & Schlesinger, 1972; Spearman, 1923), and models excluding application (Evans, 1968; Winston, 1970) but including all other sub-processes against experimental evidence. Adult subjects were tested in three different types of problems (verbal, geometric, and people-pieces problems), measuring their reaction times when varying the number of terms (nothing, A, A:B, A:B::C) appearing before the chronometer started. By a multiple regression analysis of these reaction times, Sternberg showed that the reaction time data were better explained when mapping was included, along with all the other sub-processes. However, the model that explained best participants' reaction times was a model with exhaustive inference sub-processes but only partial mapping and application sub-processes.

The framework of multiple regression of experimental reaction times to models has also been used by Sternberg and collaborators (Sternberg & Nigro, 1980; Sternberg & Rifkin, 1979) to study the sub-processes used by children of various ages. Sternberg & Rifkin (1979) showed that 8-year-olds did not use the mapping component while reasoning by analogy, while older participants (i.e., 10-, 12-year-olds and adults) used it with problems involving attributes that were separable from the whole picture (e.g., hats and bags in pictures of characters), but not in problems involving integral attributes (e.g., height or weight). The difference of usage of mapping in younger and older participants was linked to their ability to detect a higher-order similarity between the relations between A and B on one hand, and between C and the solution on the other. Another notable aspect of their work is the difference in the completeness of the componential sub-processes employed by the participants of different ages. The models best explaining children's reaction times all confirm Sternberg's (1977) results, application and mapping not being exhaustive. However, children differed in the completeness of the encoding and inference processes. Indeed 8-year-olds had both their encoding and inference processes incomplete, when 10-year-olds had only the latter incomplete and older children both of them exhaustive.

To conclude, what seems to separate younger from older children's processes is their ability to encode and maintain the representations of the domains presented. The difference between older children and adults' processes resides in the inability of the formers to genuinely use the mapping process to put the two domains into correspondences.

III.b. Theories of adult analogical reasoning

The most studied process in analogical reasoning is the mapping process, thought crucial for the success of the comparison between the two domains and the resolution of problems by analogy. Hence, most theories and models have focused on this process, giving little or no insight on the other sub-processes. In this subsection we review the most preeminent theories of analogical reasoning, i.e., the Structure Mapping Theory (Gentner, 1983, 1989), the Multiconstraint Theory (Holyoak & Thagard, 1989), the theory behind Learning and Inference with Schemas and Analogies (Hummel & Holyoak, 1997), and Copycat and Tabletop (French, 1995; Mitchell, 1993), and finally the Path-Mapping Theory (Salvucci & Anderson, 2001).

Structure Mapping Theory

The Structure Mapping Theory (Gentner & Markman, 1995, 1997; Gentner, 1983, 1989) assumes that the domains which are compared in analogical reasoning are represented by the subject as relational structures with objects (e.g., a dog, a ball), attributes (e.g., hairy, small), and relations between the elements (e.g., catches) which can be syntactically described as a propositional network of concepts, either under the form of predicates (i.e., attributes and relations) or of arguments to these predicates (i.e., objects). Attributes and relations distinguish themselves from each other in the number of arguments they can take: attributes are predicates with only one argument (e.g., small(ball)); relations are predicates taking two or more arguments (e.g., catches (dog, ball)). Gentner also distinguishes first-order predicates from higher-order relations: the first ones take objects as arguments, the second, relations.

Therefore, analogical reasoning is about comparing two of these domains: the mapping process is the process that finds the one-to-one correspondences between the objects and the known relations in the two domains, based on their names, the number of arguments of the predicates, etc. These correspondences are then used to project new predicates from the base to the source (i.e., inference). However, the analogical mapping uses a set of rules to fit the definition of analogy given by Gentner (1983) to be purely relational: attribute correspondences tend to be discarded in the evaluation of the mapping, and relational predicates between corresponding objects tend to be preserved, based on the fact that higher-level relations guide the mapping of lower-level relations (the Systematicity Principle) and that corresponding relations have corresponding objects. Thus, higher-order predicates are favored over first-order predicates, and determine which lower-order relational predicates are transferred and which are not.

This theory argues that subjects first find local matches between objects and relational predicates on the basis of a set of rules (i.e., if first-order relations or attributes are similar, the subject hypothesize that they match, then he checks if their arguments are of the same type (objects or relational predicates). Then, they create global matches on the basis of these local matches, using possible mappings of the different entities in the two domains, thus creating different system mappings including possible inference in the target (i.e., different possible interpretations for the comparison). Finally, subjects evaluate the different interpretations that were found, and choose the best one. To do this they use several types of evidence: the clarity of the mapping (i.e., one-to-one mappings are preferred), the number of potential inferences that can be drawn, and the depth of the relational structure preserved in the comparison in terms of the number of different predicates mapped, the level of these predicates (i.e., elements, first-order or higher order relations) higher level predicates being preferred, and how much they are connected (the Systematicity Principle).

The strong focus of this theory of mapping on relational predicates is supported by experimental evidence showing that adults, when presented with analogical comparisons, attended more to relational similarity than to attribute similarity to interpret it, in the case of true analogies and relational metaphors as in the case of metaphors focusing both attributional and relational similarity (Gentner & Clement, 1988; Gentner, 1980). Evidence for the Systematicity Principle effects on mapping and inference comes from Clement & Gentner's (1991) study described above.

Multiconstraint theory

The multiconstraint theory (Holyoak & Thagard, 1989, 1997) is one of the major alternative to the Structure Mapping Theory, even though it is very close in its assumptions about the key roles of relational similarity (along with superficial similarity) and systematicity constraints (called the structural constraint). The authors also add a third constraint: pragmatics constraints (i.e., the goal currently under consideration). These pragmatics constraints make the subject more aware of the features of the source and target domains that are relevant to his goals. Another goal of this theory is to account for both access and mapping aspects of human analogical reasoning.

This theory assumes that subjects generate local mapping hypotheses between the two domains and uses a set of constraints on the local mapping hypotheses to be included in their global mapping of the two domains at the same time. The mapping hypotheses which are generated are limited by a structural constraint to object to object and predicate to predicate matches. Object to predicate, and predicate to object match are discarded. Correspondences between objects that do not play the same role in the relations are also discarded by the subject. For instance, in the comparison of a cat chasing a mouse to a boy chasing a girl, the subject only generates local matches between the elements chasing and the elements chased, but not between a chasing and a chased element. Structural consistency also guides the subject toward certain types of mapping hypotheses. Lower-order predicates which are matched enhance the probability of the mapping hypothesis between two corresponding higher-order match to be chosen and vice versa. Thus, in the mapping between two situations, say a cat chasing a mouse causing the mouse to accelerate its running pace, and a boy chasing a girl causing the girl to accelerate her running pace, if the mapping hypothesis between the two "chasing" relations is envisaged, it will increase the probability of the mapping hypothesis linking the two "cause" instances to be also picked. The one-to-one mapping constraint has, on the opposite, an inhibitory effect: it decreases the probability of several hypotheses involving the same objects to be chosen by the subject at the same time. Similarity and purpose (i.e., the goal of the subject) are also constraints on the mapping: hypotheses involving semantically similar elements or which are goal relevant are more likely to be chosen. The subject arrives to a global mapping by picking the different local hypotheses that permit a coherent global mapping which takes the more of these constraints into account.

The addition of pragmatic constraints on the way mapping are drawn is supported by evidence by Spellman & Holyoak (1996). They showed that participants whose goals were experimentally manipulated and who were asked to draw analogies which were ambiguous relative to their mapping made different objects in the two domains compared correspond, according to their ongoing goals.

Learning and Inferences with Schemas and Analogies (LISA)

The LISA model (Hummel & Holyoak, 1997, 2003, 2005) is an effort to take into account both psychological and neural constraints that arose from the literature on analogical reasoning. It tries to account for the flexibility of human analogical reasoning and its structure sensitivity at the same time. It also tries to capture the psychological limitations on analogical reasoning, such as working memory capacity limits and time dependency, sensitivity to problem presentation and strategic factors, while keeping the same constraints on analogical reasoning (structure sensitivity, one-to-one mapping, semantic similarity, and pragmatic centrality).

LISA assumes that the knowledge of the subject is distributed. Hence, semantic knowledge is decomposed in objects, semantic knowledge about these objects, their roles in the relations, the relations themselves, the structure of the relations considered or propositions. These different levels of knowledge are represented by the subject in a hierarchical form: semantic features are linked to objects (representing objects and attributes), objects are linked themselves to role-fillers (the roles of objects in relations) which are linked to sub-propositions (representing the object-role binding), and sub-propositions are linked to propositions (representing relations). It also assumes that the representation of the knowledge of propositions is dynamical: different role-filler knowledge units and their corresponding objects are active in working memory in an out of synchrony manner to create a complete relational representation (e.g., John-lover and Mary-beloved are activated out of synchrony to represent the relation John loves Mary), this dynamics being due to lateral inhibition between different representations of the same type (inhibition component of working memory). Object-role bindings and relations are stored in long term memory with the means of sub-proposition and proposition knowledge units respectively. The sub-proposition knowledge is able to recreate the dynamics of activation patterns of object, semantic features and role-fillers in working memory. Propositional knowledge is what binds sub-proposition knowledge units in long term memory, and can also be bound in higher-order relations. The last type of representations assumed by this theory is schemas, which can be learned by the comparison of different structured representations which are analogous.

When the subject compares two domains, one domain (the driver) leads the mapping process, while the other domain (the recipient) is activated in working memory by the corresponding activity in the subject's representation of the driver domain. Thinking of the driver domain leads to propositions in this domain being activated in turn. It is assumed that propositions which are relevant to the subject's current goals will be activated earlier and more often than other propositions in memory. This activation of propositions then activates corresponding sub-proposition knowledge in turn. Objects and role-fillers along with semantic features which are linked to the activated sub-propositions are also activated in working memory in a dynamic fashion. Higher-order propositions are treated the same way, except that only one hierarchical level is activated at a time, and that propositions activated by the activation of a higher-order proposition as arguments are chunked (i.e., the detail of the structure they have is not available to the subject for treatment).

The activation of the recipient representation by the subject is the result of the activation of semantic features in working memory, which are linked to objects both in the driver and in the recipient. Thus, when the subject thinks of the semantic features in the driver domain via its own object and role-filler units, this activates the corresponding representations of objects and role-fillers in the recipient domain in synchrony of those in the driver domain, generating a mapping between these representations. During this activation, there is a competition between units of the same class, and cooperation between the units belonging to the same propositions, to model the dynamics of the representation of the driver. The co-activation between the representations of the same class in the two domains thus creates a full mapping of the two domains.

However, to working memory limits analogical reasoning: the number of activated sub-propositions in the driver that are activated simultaneously in working memory is limited to 4-6 sub-propositions for adult, healthy participants.

The LISA theory accounts fairly well for a great variety of phenomenon related to analogical reasoning: the role of similarity in access and inference (Ross, 1987, 1989), the differential access of close and far analogs (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980, 1983), the relevance of goals in the process of mapping (Spellman & Holyoak, 1996), the difficulty people encounter with unnatural analogs (Keane, Ledgeway, & Duff, 1994), and ontogenetic changes in the ability to learn new structures (Halford & Wilson, 1980).

Copycat & Tabletop

The theory behind these models (French, 1995; Hofstadter and the Fluid Analogies Research Group, 1995; Mitchell & Hofstadter, 1990; Mitchell, 1993, 2001) is that high-level perception (i.e., understanding of situations and similarity perception between highly structured inputs) emerges from the interplay between perception and a highly flexible conceptual system. This is achieved in a dynamic fashion, using parallel processing of different lower-level perceptual processes to construct a systematic representation of a problem at a higher level. These two models are based on similar architectures but evolve in different domains. Copycat uses proportional analogies between strings of letters, when Tabletop uses analogies between spatial settings of objects of everyday life. Due to their probabilistic functioning, they are well suited to model inter-individual differences in analogy-making (Mitchell, 1993).

These models postulate a distinction between three cognitive modules: the conceptual system in long term memory, with conceptual representations in a network, a working memory system were the temporary representations of the analogical problems are progressively built and destroyed until they stabilize, and different perceptual and higher-level hypothesis testing procedures which represent what the subject is able to perceive from the materials presented. It is the dynamic interaction between these three sub-systems that permits the subject to have a structured representation and interpret the analogies. The conceptual representations in the conceptual network are linked by association which allows slippage from one conceptual representation to another highly associated one (e.g., between the concepts of successor and predecessor). Activations of these representations are thought to be a function of their relevance to the problem at hand for the subject, and their association to other relevant concepts. The association strength between the concepts evolves during problem solving, depending on the dynamic representation of the problem by the subject. Slippage from one concept activation to another, highly associated concept is more or less probable depending on the other concepts activated when solving a problem and the subject's interpretation of the problem and the correspondences he perceives between the domains. Thus the conceptual network of the subject is believed to be highly flexible.

The structure of the representation of the problem in working memory is dynamically obtained by the engagement of his conceptual knowledge and the perceptual hypothesis testing procedures in parallel, and contains different types of information about the problem at hand: a description of the problem's elements, their interrelations, groupings of several objects, and correspondences between objects and group of objects (i.e., mapping). These representations are built as the result of the hypothesis testing procedures, which is the way for the perceptual system to determine some low level structure between elements within and between domains (i.e., their outputs correspond to the descriptions, interrelations, groupings and correspondences mentioned above), and result in the strengthening of these representations as a function of the degree of associations of related concepts in the conceptual network of the subject, the consistency of this representation (how frequently it has been found during the exploration of the different parts of the problem), and the activation of related concepts. The different perceptual hypothesis testing procedures are believed to be run based on their relevance to the structures which are built in working memory and their strength, leading to emergent, coherent representations of the problems in the subjects mind. Thus hypotheses about the structure which comfort the present representation of the problem’s structure are more probable to be run than irrelevant ones. In summary, representations of the problems by the subject reflect the coherence actively sought between the long-term knowledge he has acquired and what he perceives from the problem. As changes in the high level representations of the subject only after hundreds of hypothesis testing procedures run, the theory describes low level, highly parallel cognitive activities resulting in higher level, serial activities.

The Path-Mapping Theory

The Path-Mapping Theory is an attempt to integrate analogical mapping with constraints on problem solving in the ACT-R architecture (Anderson & Lebiere, 1998), a production system which leads to tractable "actions" which can be compared to real world behaviors in different tasks, such as eye-tracking data.

The knowledge of subjects is believed to be represented in a semantic network with semantic relations linking relations, roles and objects, and semantic knowledge about these objects, roles and relations, similarly to the knowledge network in the LISA theory. One of the parameters captured by the knowledge network of humans is how similar concepts are on a semantic dimension. These concepts are activated through the processing of the problem, and the number of concepts activated at the same time in working memory is limited. In addition to this semantic knowledge, subject also has to engage his procedural knowledge about how to act when certain conditions are met (i.e., if this information is met, I have to do that). These rules determine which action is undertaken at what time by the subject. The subject triggers this procedural knowledge according to the goals of the task he has to perform. The subject gives an answer when the main goal of the task if achieved. Mapping is effectuated through such behavioral rules by mapping one object at a time. This is done by finding the path of a source object to its highest order relation in the knowledge structure of the representation of this domain, and then finding the correspondent of this path in the target, based on the similarity between the source and target chunks of knowledge. These correspondences between the two paths are stored and reutilized for the mapping of other objects, leading to a more global mapping if needed to solve the task. Organizational knowledge is also invoked by subjects to coordinate the mapping of the different domains with task specific actions such as encoding the information of the problem and responding.

This theory predicts the same effect as the Structure Mapping Theory and the Multiconstraint Theory — namely the Systematicity Principle and pragmatic effects due to the goals of the task at hand — and also surface similarity effects interacting positively or negatively with the mapping between the two domains. It successfully explains the same phenomena found in the analogical reasoning literature as the theory behind LISA (Hummel & Holyoak, 1997; i.e., isomorphism, similarity, pragmatic centrality, multiple possible mappings for a single analogy, facilitation effect of an initial correct correspondence, difficulty with unnatural mapping problems, and the possibility to map predicates with different numbers of arguments) along with other phenomenon not accounted for by LISA (the generation of non isomorphic mappings, the preference for many-to-one mappings over one-to-many mappings, and the ability to map complex analogs rapidly). It also accounts for the eye-tracking data gathered in a story mapping experiment (Salvucci & Anderson, 2001) in which subjects had to put into correspondences the different parts of two analogous stories. Participants started responding about the correspondences of subparts of the problem before encoding the totality of the stories, showing that they could split the mapping process, just like the path-mapping does. The theory also accounts for the saccades between the different parts of the stories to be mapped.

Comparison of the different theories

All the theories presented above share commonalities, but have their own ways to deal with questions about cognitive processing during analogical reasoning. The following comparison will be made on the basis of the following points: what the representations are for each theories and how they are built, how the mapping is effectuated, the psychological plausibility of the computations described in terms of cognitive limitations, the ability of goals to influence the reasoning process (which will be of crucial importance for this dissertation, see section V of this chapter), and the time course of the computations effectuated by the different sub-processes.

The encoding of the domains compared, as described in subsection II.a. of this chapter, is the sub-process that permits the building of a mental representation from information that is gathered by the subject about the problem. This issue has been avoided by most of the theories presented above, assuming that representations were common to every subject, and take a variant or another of the symbolic form, with predicates and arguments. The only theory that tackles this problem is the one behind Copycat and Tabletop which postulates a direct interaction between a flexible conceptual system which drives and is modified by a perceptual exploration of the problem. This exploration is thought to follow many leads in parallel, and the structure of the representation to arise from this parallel search. This way of representing the structures of the problems is able to explain the differences of interpretation that are observed in human participants in ambiguous problems (Mitchell, 1993).

The mapping process is also described in different ways in these different theories. Gentner & Forbus (2011) classified these different theories using this criterion. We can use two broad classes they defined to describe the present theories: top-down and local-global mapping processes. The first class is the class of theories that argues that subjects first identify local relations in the source domain, and then try to find correspondences in the target domain. The mapping is thus built incrementally by finding all the correspondences between the source and the target domain. The theory behind LISA predicts this kind of mapping, as the mapping is performed by the activation of substructures of the driver domain in working memory by the subject, which finds the correspondences in the recipient domain basing his choice on the semantic properties of the elements that are common to both domains. The Path-Mapping Theory is another example of this class, predicting the subjects would start by aligning each object of the two domains in term, considering only subsets of the relational structures, subsets which are linked to the objects compared. The second class predicts a local to global mapping by participants: subjects are believed to find all possible matches between the two domains in parallel, on the basis of the features and relations in the two domains compared. After this, they select the mapping that best suits the constraints on analogical reasoning to find the best mapping. Examples of these theories are the Structure Mapping Theory and the Multiconstraint Theory. The theory behind Copycat and Tabletop lies somewhere in the middle between these two broad classes. In this theory, participants follow different mapping leads at the same time, but during the building of the representation of the problem, they are more and more influenced by higher-level local relations in the way they interpret other relations, which can be compared to what LISA predicts.

These mapping sub-processes deal differently with the question of psychological plausibility of the computations they describe. Indeed, working memory capacity sets limits on the number of comparisons that can be done at the same time, and the structures that can be kept active (see subsection IV.b. for empirical evidence of this assertion). Thus the mapping sub-process as described in the Structure Mapping Theory, and the Multiconstraint Theory seems to be unlikely in a cognitively limited human mind. Indeed, the fact that they envisage all the possible mappings between the domains compared would exceed by far the working memory capacity of human individuals. The same problem is true for Copycat and Tabletop, as they do not give any upper limit of the number of items that can be kept active at the same time. LISA and the Path-Mapping Theory however envisage this possibility of limiting the number of relations and objects that can be processed at the same time. The first accounts for this by a limited number of relations activated at the same time, when the second accounts for it by a difficulty of reactivating knowledge in working memory, depending on the frequency of use of this knowledge and decay of its activation in working memory. However, all but one of the above-mentioned theories makes the prediction that the mapping is necessarily complete. The only theory predicting that sometimes the mapping is incomplete is the Path-Mapping Theory which states that when a subject has enough information to complete the task at hand, the mapping process stops.

It follows from the last paragraph that it seems that goals of a task are relevant when studying analogical reasoning. The motivations of a subject to perform a mapping have been shown to influence the outcome of this sub-process (Spellman & Holyoak, 1996). This guiding of the mapping by goals has not been acknowledged in most of the theories presented above. Neither the Structure Mapping Theory, nor Copycat or Tabletop predicts that subject would make different mappings on the base of the goals they are pursuing. However, the three other theories raise this possibility. The Multiconstraint Theory states that goals will influence the mapping between the different entities in the domains compared, biasing the mapping toward correspondences that fits the goals of the subject. LISA predicts that the frequency of activation in working memory of relations, i.e., the attention of the subject toward certain parts of the structural information of the domains, can be modulated by the goals of the subject. The Path-Mapping Theory states that not only participants' mapping is affected by goals, but also their encoding of the domains and responding.

From this comparison, it is apparent that the different theories make different predictions about how the information is used and operated on during analogical reasoning. All models have their strengths and weaknesses, even if some consensus about what the outcome of the analogical reasoning process should be in terms of the constraints it has to take into account (one-to-one mapping, the Systematicity Principle, and parallel connectivity, i.e., the fact that corresponding relations have corresponding arguments). However, these theories do not say much about how this mature reasoning arises from incompletely developed analogical reasoning in children. This issue is the topic of the next subsection.

III.c. Developmental hypotheses of analogical reasoning

The following subsection presents the main hypotheses about the development of analogical reasoning, i.e., the Relational Shift Hypothesis (Gentner & Rattermann, 1991), the Relational Primacy Hypothesis (Goswami, 1991, 1992), and the Relational Complexity Hypothesis (Halford, Wilson, & Phillips, 1998; Halford, 1993).

The Relational Shift Hypothesis

Gentner & Rattermann (1991) introduced the "relational shift" hypothesis about the development of analogical reasoning. According to them, a relational shift occurs during childhood: children first process the similarity between objects and only after a developmental change are they able to process similarity between relations. Several findings by Gentner and other researchers support this hypothesis. Gentner (1988) reported results about the interpretation of metaphors in children. She found that 5-year-olds preferentially interpreted metaphors in terms of featural similarity, whereas adults mainly used relational similarity to express the meaning of metaphors. Nine-year-olds gave in-between explanations, using both relational and object similarity, thus, apparently showing a state of saccade between the two types of focus. Similar findings were obtained by Billow (1975) in 5- to 13-year-olds. In a similar vein, Gentner & Toupin (1985, 1986) showed that children aged 6 were not affected by higher-level relations (i.e., a moral), only by the surface similarity between the objects, when performing a mapping task, whereas 9-year-old children were affected both by surface and higher-order relational similarity. The same effect of surface similarity was found in 5-year-olds in an analogy problem-solving task (Holyoak, Junn, & Billman, 1984). Children were affected by the physical resemblance of the objects to be matched.

However, as mentioned by Richland et al. (2006) and Thibaut et al. (2010a), the reason for this shift remains unclear. Several hypothesis are proposed by Gentner & Rattermann (1991): a general maturational process such as the one proposed by Piaget et al. (1977), increase in domain knowledge, or the acquisition of mapping strategies. These different accounts lead to different predictions. The general ability account predicts a general change in cognitive abilities at a certain age. The domain-knowledge account, favored by Gentner and colleagues, predicts differences between the acquisition of the ability to map structures from different domains, depending on the degree of expertise of the child in these domains. The strategy-learning account predicts both differences in the time of the shift between more or less familiar domains, and cross-domain facilitation due to strategy learning. Note, however, that these three explanations are not mutually exclusive. Whenever the performances of children increase through age, there is still room for improvement in the tasks used to assess reasoning ability. Thus, part of the improvement might be due to better knowledge of conceptual domains, to better strategies, or to domain general cognitive abilities.

Another explanation of this shift was given by Bulloch & Opfer (2009) who argued the relational shift was the effect of the learning of a the difference in the predictive value of superficial similarity versus relational similarity in different contexts through development. Thus, children's use of relational matches in a generalization task should increase when relational similarity is highly predictive, but should decrease in a domain where superficial similarity is more predictive. The results they observed in a generalization task using offspring (a domain in which relational similarity is more predictive) and prey (in which superficial similarity is more predictive) in 3-, 4-, 5-year-olds, and adults support their interpretation. Three- and 4-year-olds made relational matches more often than 5-year-olds and adults in the context of prey problems, but less than them in the context of offspring. This effect is mainly due to learning over time as 3-year-olds showed the same pattern in a repeated measure setting, when they were given feedback on their answers.

The Relational Primacy Hypothesis

Goswami and her colleagues argued for an inherent capability of even young children and infants to use relational similarity to drive their inferences about the world (Brown, 1990; Goswami & Brown, 1990a, 1990b; Goswami, 1991, 1992; Vosniadou, 1988). However, even if children are able to reason by analogy early in life, qualitative changes, such as metacognitive processes, occur throughout development. Goswami and Brown (1990b) tested children aged 3, 4 and 6 in a causal A:B::C:? forced-choice task (using, as foils, the same object as C with an incorrect relation, a different object with the correct relation, a mere-appearance match, and a thematic/category match) and assessing their knowledge of the causal relations in a control task. They found that, with age, the knowledge of the causal relations increased, and that the analogical performances increased accordingly. The majority of the errors made were children choosing the correct object, but associated with the wrong relation. This view of analogical reasoning development is supported by children's early ability to solve reasoning problems when surface similarity supports the mapping between the different domains (Chen, Sanchez, & Campbell, 1997; Holyoak et al., 1984), when a proper representation of the problem has been encoded (Brown, Kane, & Echols, 1986), or when the relational similarity between the problems to be compared is highlighted (Brown, Kane, & Long, 1989; Crisafi & Brown, 1986).

Relational Complexity

The relational complexity theory (Halford et al., 1998) posits that what limits the analogical comparisons that can be made is the relational complexity of the domains to be compared. Relational complexity is defined as the number of dimension relations have at the same time (i.e., the number of arguments a relational predicate takes). For example, reasoning about speed as a function of distance over time involves a ternary relation, where speed, distance and time are three arguments in this relational structure. Thus, what is limited in working memory capacity is the number of arguments feeding a relation which can be handled at the same time, called the arity of a relation. Complex concepts often involve more than four dimensions. To deal with these concepts, one has two possibilities: chunking several dimensions into a single one (but the detailed relations within the structures chunked cannot be accessed) or segmenting the concepts into several sub-concepts involving lower dimension relations. Thus the effective complexity is the lowest dimensionality allowed by chunking and segmentation that has to be processed without loss of information. The relational complexity that can be handled increases through development: unary relations can be processed by one year of age, binary relation by two (only binary relations have to be handled in proportional, A:B::C:? problems), ternary relations by five, and quaternary relations by 11.

The relational complexity theory is supported by several findings. First, children display an early competence (before the age of 5) in the classical A:B::C:? task when appropriate material and experiment procedure are used (Goswami & Brown, 1990a; Singer-Freeman, 2005). Nevertheless, when the relational complexity is increased above the threshold of binary relations, young children have lower performances (Doumas, Morrison, & Richland, 2009; Hosenfeld, van der Maas, & van den Boom, 1997a, 1997b; Richland et al., 2006). Performance is far from perfect when only binary relations are used in such tasks at early stages of development, which suggest that other factors than the clarity of the relations used play a role in the development of analogy making, such as the executive component of working memory (Richland et al., 2006; Thibaut, French, & Vezneva, 2010a, 2010b, see subsection IV.b. for a description), and knowledge accretion (Brown, 1990; Goswami & Brown, 1990b).

Conclusion

These different hypotheses focus on different factors in analogical reasoning development, but are not strictly mutually exclusive. It is even likely that knowledge accretion, metacognitive aspects, working memory capacity and its executive component play distinct roles in the development of analogical reasoning. These different factors might even interact as it is suggested, for instance, by current views of executive functions as being dependent on their substrate, i.e., the representations they operate on (Chevalier, 2010). Thus further work should aim at investigating these interactions in the development of analogical reasoning.

IV. Factors affecting analogical reasoning in adults and children

In this section, we will review the literature of factors affecting analogical reasoning and its development. Analogical reasoning is affected by a variety of factors from low to high level on the bottom-up continuum of information processing, such as the perception of the stimuli (i.e., intrinsic features of the materials, bottom-up attentional triggers), the organization of the conceptual system and language (i.e., categories and taxonomies stored in long term memory, and their labeling), the different components of working memory functioning and their limitations (i.e., short term storage and voluntary treatment of the information, including inhibition of part of the information, cognitive flexibility, and working memory refreshing) and the ability to plan strategically the task as well as metacognitive abilities (i.e., ordering and achieving the different goals of the task, knowing one's own capacities and limitations).

IV.a. Intrinsic features of the domains compared

In this subsection we review the literature on analogical reasoning and its development, with a special focus on the features of the domains compared which affect analogical reasoning. These factors are mainly surface features of the domains compared, like their concreteness (i.e., the amount of information irrelevant to the task they bring), the saliency of the relational structure, the depth of the relational structure of the domains in itself, and the distinctiveness of the goal object from the rest of the domain, as well as the surface and structural similarity of the two domains compared. For the factors which were tested both in adults and children, it seems that they affect their ability to reason by analogy similarly, but at different degrees.

Surface features of the materials compared

The properties of the domains which are used is an unavoidable source of variations in adults' reasoning, as the saliency of certain features of these domains will attract the attention of the subject, when other will not retain his attention, and generally will bias the representation of the domains in some configurations. These biases can be congruent with what is important for the solution of the problem, or not, which will lead to facilitation or difficulties to solve the problem.

Mature reasoning

A clue of the effect of surface features of the domains compared on transfer were obtained by Didierjean & Nogry (2004) by manipulating the difficulty of the solution of a source problem by varying its presentation and observing how participants were affected in their transfer of this solution to an analogous target problem. The authors showed that varying the difficulty to solve the source problem by making the structure of these elements more or less salient (i.e., present both in the diagram given and the verbal explanation, or only in the diagram) impacted the way participants encoded the source: simple source problems (i.e., when the relational structure was obvious) were encoded more shallowly and resulted in poorer transfer, when more difficult ones (i.e., with less salient structural features) were encoded in depth, resulting in more transfer of these abstract principles to the target problems.

Another surface factor affecting analogical reasoning is the concreteness of the elements composing the domains which are compared. Kaminski, Sloutsky, & Heckler (2013) defined concreteness as the quantity of information brought by a specific instance of a concept. Using this metric, they showed that the less concrete the instances analogically compared are (i.e., the less superfluous information they convey), the more transfer the participants do. However, when helped in the alignment of the two domains, the difference between concrete and generic (i.e., not concrete) instances vanishes. This was interpreted by the authors as concreteness affecting mapping: the concreteness (i.e., the amount of information brought by the material) is an obstacle in the alignment of the two domains, the non-alignable extraneous information masking the similarity between the structures of the two domains.

The systematicity (i.e., the fact that first-order relations are connected or not by higher-order relations) of the source domain also guides the analogical matches that are drawn by participants. Clement & Gentner's (1991) results show that participants rated more similar two analogous facts that were part of stories that had higher degrees of structural similarity than stories that were only similar in the fact that had to be compared (see materials in Figure 1). Similarly, participants were more prone to infer facts in the target domain that were parts of more global structures than isolated facts at the level of structural consistency between the two domains. Thus, the embedding of a fact in a relational structure influences both analogical judgments and inference.

Relational Structure of the Base Domain, *The Toms*, and the Target Domain, *The Robots*

Base: *The Toms*	Target: *The Robots*	
	Version 1	Version 2
Consume minerals with underbellies	Gather data with probes	Gather data with probes
Exhaust minerals in one spot and must relocate on the rock	**Exhaust data in one place and must relocate on the planet**	Internal computers over-heat when gather a lot of data
So stops using underbelly	*So stops using probes*	*So stops using probes*
Born with inefficient underbelly	Designed with delicate probes	Designed with inefficient probes
Underbelly adapts and becomes specialized for one rock	Robots cannot pack probes to survive flight to a new planet	**Probes adapt and become specialized for one planet**
So underbelly can't function on new rock	*So probes can't function on new planet*	*So probes can't function on new planet*

Note. Key facts are shown in italics. Matching causal information is shown in boldface. In Experiment 2, italicized facts were removed from the target.

Figure 1: Materials used by Clement & Gentner (1991)

These different studies show the effect of surface features is present at different levels in adult analogical reasoning. It can influence encoding, mapping and transfer.

Reasoning development

Children are also affected by the perceptual features of the material used to assess analogical abilities. Rattermann & Gentner (1998a, Experiment 1) used visually rich (i.e., concrete, as defined by Kaminski et al., 2013) or sparse (i.e., generic) objects in a triad mapping task (see Figure 2) using size as the relational frameworks in the domains to be compared. Three-, 4- and 5-year-olds were tested in this task and performed better in the sparse than in the rich condition. This suggests that concreteness (as defined by Kaminski et al. (2013), see above) also affects children's performance.

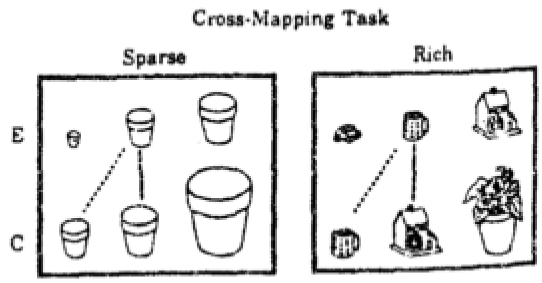


Figure 2: Materials from Rattermann & Gentner 1998a

A related study by Paik & Mix (2006) explored the effect of the distinctiveness between the objects to be matched with the other objects of the domains compared on 3- and 4-year-olds. Making the solution and the matching object in the source more distinctive from the other objects in their respective domains made children have better performances in a simple mapping task, but had the opposite effect in a cross-mapping task (when similar objects have different roles in the two domains). Vasilyeva & Bowers (2006) also have data that could be explained by the distinctiveness of the elements to be matched. They gave 3- to 6-year-olds a spatial mapping task using isosceles triangles as maps. They found that children were better able to find the target object on the basis of the map indication when it was the distinctive angle that was used to hide it than when it was one of the two identical angles.

Taken together, these results about surface features of the domains compared suggest that adults as well as children are affected in their ability to perform a mapping between two domains by the intrinsic visual characteristics of the objects constituting them: the amount of information given by the scene, but also the similarity within the domain and how easily the relational structure is inferred from the visual characteristics of the objects.

Similarity between sources and targets

We saw that the intrinsic features of the materials within domains affect analogical reasoning in both children and adults. However another kind of features, the similarity between the domains, also impacts the way people compare different domains.

Mature reasoning

The spontaneous retrieval of a source in long term memory, despite its everyday usefulness, is a notoriously difficult task (Gick & Holyoak, 1980, 1983), and is also affected by several low level factors, like surface and structural similarity between the two analogs. Holyoak & Koh (1987, Experiment 2) presented different analogical sources, varying either the structural (i.e., the constraints on the application of a solution to the problem) or the surface (i.e., the resemblance of the apparatus used to solve the problem) similarity, or both structural and surface similarity between the source and the target domains, but all sharing the same solution to the problem. They observed higher rates of correct, spontaneous application of the previously seen solution to a new, analogous problem in the condition where the to-be-retrieved source was similar both on the structural and surface dimensions. A decrease in similarity on either or both of these dimensions impaired participants spontaneous retrieval. This suggests that retrieval is dependent on both these similarity properties. Similar evidence comes from Gentner & Landers (1985). They designed a set of scenarios similar to the targets either in their first-order relations, or in both their first-order relations and their surface properties, or in both their first-order and their higher-order relations. Participants reminded more source stories that shared surface similarity in addition to analogous first-order relations, and to a lower extent stories that shared both first- and higher-order relations, than stories only similar in their first-order relation. Wharton et al. (1994) also showed that retrieval was affected by structural similarity when a competition arose between different potential analogs sharing either surface or structural similarity with the current story. However, although surface similarity can be helpful for accessing a previously encountered analog (Gentner & Landers, 1985; Holyoak & Koh, 1987), it can also be detrimental, as shown by Ross (1987, 1989). He showed that using source and target domains with same objects in different roles impaired participants' ability to retrieve a previously seen example to solve the current problem.

Both structural and surface similarities affect the mapping of one domain on the other, even if there are dissimilarities in their effects. Holyoak & Koh (1987) showed that in addition to affecting the retrieval of the source, structural similarity had an impact on the ability to draw an analogy (i.e., to transfer an already seen solution to a new problem after being given a hint to use the source story as an analog of the problem at hand). However, the surface similarity did not seem to have any effect on the use of the source after being given this hint. Nevertheless, Ross (1987, 1989) showed that surface similarity can be detrimental not only on the retrieval of a source (as presented above) but also on the use of the source, when it is pitted against structural similarity (i.e., when elements are similar in the source and target domains but do not play the same role, referred to as cross-mapping in the remainder of this dissertation).

Gentner, Rattermann, & Forbus (1993) also showed that surface similarity had differential effects on retrieval and analogical inference in adults. Participants were asked to retrieve previously encountered stories from a large set, using target stories, and to judge how much the inferences from one story of the set could be inferred analogically in another story of the set. They rated higher the inferential power of structurally similar than superficially similar stories, but retrieval was more linked to surface than structural similarity, which led the authors to conclude to a dissociation between the information that is used to retrieve analogs in long term memory and the information that is used to reason by analogy and to infer information in a new domain from another one.

From a wider perspective, the retrieval of a source analog is also altered by the similarity between the contexts of exploration of the source and target analogs. Spencer & Weisberg (1986) showed that the change of experimenter between the presentation of the source and the target analogs decreased the spontaneous retrieval of the source's solution for the solution of the target problem.

Hence, both structural and surface similarity between the domains compared have consequences on adults' analogical reasoning, but affect different processes: surface and contextual similarity seem to have a greater impact on retrieval than on mapping and transfer, which is the reverse of the effect of structural similarity. Differential effects of the two kinds of similarity are also observed depending on the fact that this similarity supports the relational alignment between the two domains or if it is pitted against this alignment on a relational basis.

Reasoning development

Children's analogical reasoning is also influenced by superficial and structural similarity between the source and the target domains. Holyoak, Junn, & Billman (1984) used a problem solving task, known as the Genie problem. In this task, they have to transfer the solution used by the genie to solve a similar problem themselves. Changing the source story in its surface similarity (adding a new character) or in the primary goal the genie was pursuing lessened dramatically the number of transfers of 6-year-olds when compared to a control group using higher surface and structural similarity.

Similar findings were obtained by Gentner & Toupin (1985, 1986). They asked 4-6- and 8-10-year-olds first to act out stories with toy dolls and then to act them out a second time with different characters. They varied the systematicity of the stories by adding or not a moral to them. The superficial similarity was also manipulated as the children had to act out the stories with different toy dolls the second time, these toy dolls having high superficial similarity and same roles, no superficial similarity, or high superficial similarity but different roles (referred as cross-mapping). Performances of the younger children were generally lower than those of the older group. Both ages were negatively affected by the decrease of superficial similarity, and even more dramatically by the cross-mapping condition in both high and low systematicity conditions. However, a difference between the two systematicity conditions appeared only in the low superficial similarity and cross-mapping conditions in older children, suggesting a developmental trend toward the use of systematicity in analogical reasoning and that it helped them overcome the most difficult mapping condition (i.e., cross-mapping). Kotovsky & Gentner (1996, Experiment 1) found converging evidence using a mapping task between triads of geometrical forms varying on the dimension of the relational structure (e.g., size, color) and the polarity of the relation (e.g., a big-small-big pattern in the source corresponding to a big-small-big pattern in the target [same polarity], or to a small-big-small pattern [different polarity]). They found main effects of both these kinds of similarity and that the ability to handle more superficially dissimilar materials developed between 4 and 8 years of age. Convergent findings come from another study by Chen (1996) which explored surface and structural similarities. Chen also manipulated procedural similarity of the implementation of the solutions (adding water or combining different items with the same goal) and surface similarity in the source and target (Chen, 1996; Experiment 2) and found a significant effect of this kind of similarity on 5-to-8-year-olds, with higher similarity supporting mapping between elements to be matched.

Thus, what might negatively affect very young children's ability to transfer a solution from one problem to another might be their inability to notice this similarity between the structures of the two problems. Crisafi & Brown (1986; Experiment 2 & 3) explored this issue in 2-3-year-olds. Children who were given hints that the two problems were the same outperformed those who did not have any explicit clue of the two problem's similarity from the experimenter. This finding was reliable, even in highly superficially dissimilar problems.

Daehler & Chen (1993) further explored which similarity aspects were determinant in children's use of a source to solve a target problem. They varied the similarity between the source and the target in several ways: resemblance between the main characters of the stories, the main themes, or the goal objects, and tested 5- and 7-year-olds. The younger group's transfer rate and reaction time were mainly affected by the goal object similarity and marginally by the theme similarity between the two domains. The older group was not affected by the manipulations of these types of similarities. Thus, goal object similarity seems to be crucial in young children's ability to solve problems by analogy.

The effect of similarity between the source and target domains is one of the most reliable finding in the analogical reasoning literature. This similarity can be helpful, especially when testing very young children, when it supports the matching between the objects and relations in the domains compared. However, it is detrimental when this similarity leads to inconsistent mapping (e.g., in the cross-mapping task).

IV.b. Features of the mental representations and the influence of the conceptual system

The evidence reviewed in this subsection show that features of the domains compared are not the unique factor influencing analogical reasoning. Indeed, the mental representations of the domains and their quality, as well as their psychological characteristics linked to the organization of the conceptual system (categorization of the elements composing them, perceived semantic distance between the domains, and use of language to describe the domains) have a deep impact on analogical reasoning

Mental models formed from the two domains and their similarity

The precedent studies about features of the domains compared showed that similarity between the domains compared, either superficial or structural, influenced analogical reasoning. However, the studies presented below tend to show that what is really important is not the intrinsic similarities of the domains, but the similarity between the representations of these domains, constructed by the participants.

Mature reasoning

The similarity between the representations of the domains built by participants seems to be an important factor in the ability to compare them and find correspondences between them. Day & Goldstone (2011) discussed the distinction between intrinsic concreteness of the stimuli and the concreteness of the representations of these stimuli. They observed a transfer of the knowledge acquired about a fairly simple physical system to a novel task, apparently very dissimilar. These results were influenced by the similarity of the mental models constructed: when keeping the similarity between the source and the target constant, the authors observed better transfer performance when mental models constructed from the interaction with the first simple physical system (i.e., the source domain) leads to a representation that has the same direction of variation as the target domain than to an opposite direction of variation.

Lee & Holyoak (2008) also addressed the question of whether people utilize mental causal models and how the similarity between the causal structures in the two domains compared influence inference. They showed that the presence of a preventive cause (A tends to cause B not to happen) shared by both analogs increases similarity judgments of the two analogs but decreases the inferential power of the analogy (if a preventive cause is present in both analogs, participants tend to have lower confidence in inferences made in the target). This effect is suppressed when only generative causes are included in the target. The reversal of a relational preventive cause (e.g., if having more hormone A than hormone B prevents the development of a certain type of glands, what happens when something has more hormone B than hormone A?) augments inferential power from a source to a target and has the same level of inferential power as a fully generative source (in which all causes are positively affecting the presence of an effect).

Similarly, Bassok, Wu, & Olseth (1995) showed that participants reinterpreted the relational structure of their problem to fit their assumptions about the cover stories used to present the problems to them. They used two types of cover stories for source and target problems, one eliciting an interpretation of an assignment as a pairing between two sets (e.g., doctors from different hospitals have to work in pairs) and one eliciting an interpretation of an assignment as someone getting something from someone (e.g., students given prizes by their professor). The assignment equations from the source domain had then to be transferred to a new, analogous problem. Problems eliciting different types of interpretations were experienced as non analogous by participants, even though they were.

These empirical works support that dissociation can be made between the intrinsic similarity or dissimilarity between two domains and the one that is processed during analogical reasoning, which also depends on the interpretation of the domain that is done by the subject.

Reasoning development

The extent to which the features of the mental models formed by participants during the analogical task influence their transfer has also been investigated in children. Brown, Kane, & Echols (1986) contrasted the effect of different conditions on 4- and 5-year-olds analogical transfer of the solution of the Genie story in analogous problems: in the Explicit Goal Structure condition, they helped children construct a mental model of the source that integrated the relational structure of the Genie story, and compared it to a Recall condition in which children had only to retell what they remembered from the story, and a Control condition in which they had nothing to do but transfer the solution to the new problem. In their experiments, performance was higher in the Explicit Goal Structure and Recall conditions than in the Control condition, but these first two conditions did not differ reliably, although a slight advantage for the former on the latter appeared. However, when separated on the basis of their ability to recall the goal structure, the children in the Recall condition who were more goal-centered in their explanations were more successful in transferring the solution than those who did not give goal-related explanations. In their third experiment

Brown et al. (1986), after assessing children's ability to recall the goal structure of the Genie problem, separated them into three groups: good goal structure "recallers" and a control group of children not recalling the goal structure were directly given the transfer problem, and a third group of poor goal structure "recallers" were administered the Explicit Goal Structure questionnaire to help them form a goal-centered mental model of the source story. Both the children in this latter condition and the good "recallers" achieved transfer to a greater extent than those in the control condition. Moreover, these children did not have any difficulty to recall the goal structure when prompted to do so, suggesting an attentional failure toward the goal structure rather than an inability to recall it.

Similar findings were obtained by Crisafi & Brown (1986; Experiment 4 & 5) whose study tested 3-4-year-olds in a context of transferring the solution from a "game" to another. In one condition, children were explicitly given the rules by the experimenter and were asked to tell these rules to a puppet in order for it to use this rule. This condition was compared to a simple transfer condition, without rule telling either by the experimenter or the children. Similarly to previous results, children in the first condition had higher performances than those in the second one. Therefore, telling the rule to a puppet in order of it to be able to use it helped children to construct an efficient mental model.

These results suggest that it is in fact the representations of the domains and their structural similarity, in addition to the ability of participants to attend to the correct aspects of the representations that supports the mapping between the two domains. This could explain Sternberg's (1977) observation of a correlation between accuracy and time spent encoding the analogical problem. However, the similarity between the representations of the domains is often correlated to the visual similarity between the different components of the domains, which make this factor difficult to manipulate.

Quality of the representation of the structures compared

The quality of the representation in terms of clarity of the relational structure of the domains encoded, in contrast to shallower representation, seems to impact deeply the way people draw analogies. This better quality is usually attained by focusing participants on the relational structure of the domains, for instance by using comparison between similar structures. Generally, and as will be seen in the studies reviewed below, the clearer the relational structure is represented, the better analogies are processed by adults and children.

Mature reasoning

The perceptual modality used to encode the source and the target might be important in focusing participants' attention toward the relational information. Markman, Taylor, & Gentner (2007) showed that the ability of participants to retrieve a previously encountered proverb with a new proverb as a cue differed depending on the presentation of these proverbs was in the visual (i.e., reading) or auditory modality. Participants hearing the proverbs recalled more relational information from the previously encountered proverbs in the long run than those reading them. There was also a positive correlation between the quantity of relational information used to define the filler problems and the quantity of analogical information recalled. Definitions using surface information were also more frequent in the visual than in the auditory modality when the quantity of relational information used did not differ. Taken together, these results suggest a bias to extract purer relational information when the material is encoded in the auditory than in the visual modality, influencing later retrieval of an analog.

These results, showing that people encoding analogous proverbs in the auditory modality are more focused on relational information, retrieve more relationally similar source proverbs than in the visual modality, and thus might have a representation of the relational structure of a better quality, are consistent with Holyoak and collaborators' (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983) accounts of a better encoding of the source's relational structure positively affecting later spontaneous retrieval. These different studies examined the effect of a focus on relational information while encoding the to-be-mapped analogs, using comparison to enhance this structural encoding. Gick & Holyoak (1983) were the first to explore this possibility: they asked their participants to compare two source stories before giving them the target problem. Performance was greater when comparing two analogs or two dissimilar stories than when only a single source analog was given. This performance enhancement is most likely due to a better encoding of the relational structure of the source, as participants gave more relational descriptions in these conditions than in the single story condition. A verbal description of the convergence principle used to solve the problems or a diagrammatic representation of this principle also enhanced participants' spontaneous transfer of the solution by the means of a better encoding of the relational structure. Catrambone & Holyoak (1989) showed that this effect was due to the comparison of the two analogs and not to the mere exposure to two analogous stories, and that this effect was robust even after a delay of a week between the exposure to the sources and the target problems. A convergent piece of evidence comes from Clement, Harris, Burns, & Weatherholt (2010) who studied the eye movements of participants in a similarity judgment task after giving them multiple examples of the same relational structure. They found that giving two analogous pictures and asking participants to compare them prior to the judgment task per se lowered the attention toward structurally irrelevant objects that were similar at the surface level in the two scenes during the judgment task, when compared to participants only having to look at two analogous scenes prior the judgment task. Thus, encoding of the source seems to be affected by the comparison of different instances of the same relational structure.

However, a better encoding of the to-be-retrieved sources is not the only factor affecting the retrieval of a source. Loewenstein and colleagues (Gentner, Loewenstein, Thompson, & Forbus, 2009; Kurtz & Loewenstein, 2007; see Loewenstein, 2010 for a review) showed that a better encoding of the relational structure of problems by comparing them is also a factor determining retrieval of source analogs, in autobiographical memory as well as in a set of pre-given source stories. The effect of comparison was effective on encoding as participants showed better comprehension of the target problems than those seeing both problems without comparing them.

These studies suggest that a better representation of the domains' structure, either by the perceptual modality used to encode the information, or by the alignment between different instances of the same structure, helps people retrieve analogous instances of a relational structure.

Reasoning development

The Progressive Alignment hypothesis states that it should be easier for children to achieve complex, remote mapping by first giving them simple examples of the higher-order relation, and then progressively giving them more and more distant mapping examples. Thus, by comparing the different instances but first keeping a common ground between them, the structural alignment between the domains to map should become more obvious and easier to handle for them. Kotovsky & Gentner (1996, Experiment 2 & 4) used a Progressive Alignment procedure to help children acquire the ability to handle cross-dimensional analogies (e.g., matching a big-small-big pattern to a white-black-white pattern). Indeed, 4-year-old were helped by the experimental procedure consisting in first being presented with the Same-Dimension trials and only then the Cross-Dimension trials. In this condition, they outperformed the control group of 4-year-olds (presented with Same- and Cross-Dimension trials in a random order) in both sets of trials. In the fourth experiment, children were trained to achieve a criterion in the Same-Dimension trials before being given the Cross-Dimension trials. Children trained with the Same-Dimension trials performed better after the training than before. The effect of Progressive Alignment was found again in an A:B::C:? task (Anggoro, Gentner, & Klibanoff, 2005). Progressive Alignment thus seems to efficiently focus children's attention on the relational information, and help them solve analogical problems. However, this effect might be due to the comparison of different instances of the problems helping children understand the constraints on the solution (Goswami, Leevers, Pressley, & Wheelwright, 1998).

Comparison between different problems of the same type is not the unique comparison useful to children. Indeed, the simultaneous comparison of different instances of the same relation as source before the solution of an analogical problem has also been shown to foster attentional focus on the relations rather than the objects composing them in children. Christie & Gentner (2010) tested 3-to-4-year-olds in a Relational Matching to Sample task in which children had to find between two cards, the one that was the most similar to the one presented as a standard. They found that children did relational matching more when two standards were compared simultaneously than when they were presented sequentially or only one standard was presented.

Together, these results support that comparison, either between different sequential instances of further and further examples, or between different instances of the same relation simultaneously, help children construct a representation that is more focused on the relational information than on the objects composing them when reasoning by analogy, as was shown in adults when they have to retrieve a source.

Semantic distance between the domains compared

Other characteristics of the mental representations of the domains compared, linked to the organization of concepts in long term memory, influence the ability to draw analogies. For instance, it is intuitive that the semantic distance between two domains compared is a factor in analogical reasoning. It is more difficult to draw an analogy between the hunt of a wolf pack and the ball-seeking behavior of a football team, than between the same wolf pack and a group of lions, even though both make reference to a "hunting" behavior. The following review show examples of this factor interacting with analogical reasoning.

Mature reasoning

Semantic distance is a blurry concept: it is used by various authors to talk about different dimensions of variations of this distance in analogical transfer. This was acknowledged by Barnett & Ceci (2002) who proposed a taxonomy for semantic distance. They divided the different dimensions of variations along two groups: variation of content and variation of context for the application of knowledge in one domain to another. The first group includes dimensions such as the type of learned skills, the dependent variable on which the expected performance change should occur, and the memory demands elicited by the task. The second group refers to the dimensions of knowledge domain to which the skill (here, "skill" should be seen in a broad sense) is to be applied, the similarity of the physical, temporal, functional and social contexts of the two domains, and the modality used in the two domains.

The knowledge domain distance has been of special interest in analogical reasoning researches and has been proven to activate differentially the brain in judgments of the validity of A:B::C:D analogies. Vendetti, Knowlton, & Holyoak (2012) assessed participants' judgment of validity of A:B::C:D analogies with near and far domains (defined as both A and C on one hand, and B and D on the other, belonging to the same category in the case of near analogy, or to different categories in far analogy, the relation being kept the same). They observed a general decrease in hits and increase in false alarms with the increase of semantic distance. This factor has also been shown to modulate the activation of brain areas and the dynamic of the brain processes during analogical judgment, with the semantic distance between the domain measured with a Latent Semantic Analysis (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Kmiecik & Morrison, 2013).

In conclusion, we have seen both behavioral and neural evidence that near and far analogies are processed differently by adults: they rate far analogies less valid than close analogies, and that brain areas that are usually engaged in relational integration are more activated by far than near analogies.

Reasoning development

The effect of domain knowledge distance is also visible in children. Chen & Klahr (1999) tested the transfer of the principles of controlling variables in scientific experiments in children (8-, 9-, and 10-year-olds) within and across domains. To do this, they were introduced to the way one domain (e.g., springs) worked during the familiarization phase of the experiment and then were assessed on their ability to control variables to test hypothesis in this domain. On a subsequent test phase, they were asked to transfer the same ability in other domains (e.g., sinking, slopes). Finally, children were tested on their ability to choose between two settings the one which was suitable for hypothesis testing in distant and close domains. The younger group of age showed more transfer in close domains than in remote ones, and only the older group was able to transfer to semantically distant domains the knowledge they had acquired.

Thus, semantic distance, defined here by the distance between the knowledge domains which have to be compared, affects both children and adults in their ability to evaluate analogies and transfer relational structures from one domain to the other. The greater the semantic distance perceived, the more difficult it is to draw analogies.

Categorization and concepts of the elements composing the systems compared

The characteristic of semantic distance between the two domains compared is not the only psychological feature of representations that influence participants' ability to reason by analogy. Another one is the category relations between the different elements composing the problem. However, these two types of factor might be partially overlapping, the difference of categories between the source and target elements contributing to the semantic distance between the two domains.

Mature reasoning

A series of experiment by Green and collaborators examined the influence that the categorization of the domains' elements had on the mapping process.

In the first of these studies (Green, Fugelsang, & Dunbar, 2006), participants were presented a four-word stimulus (forming a square) and had either to judge if the pairs of words presented in rows were of the same category, or if there was an analog between the four words. After this judgment, they had to name the color of the ink of a word that was either of the same category as words presented in rows, or not. Results showed that participants responded more slowly (i.e., that the automatic category activation interfered with the color labeling) in both category and analogy judgment conditions. However, reaction times were only slower in the analogical judgment condition when the word was a categorical instance of the relation between the words pairs formed in columns. There was no difference when the words were unrelated. This suggests that categories between elements of the domains (i.e., words presented in rows) are activated in both category and analogy judgment tasks, but that the relations between the words presented in columns are only activated in the analogy judgment task, thus facilitating later activation of these concepts.

Similar findings were found by Green et al. (2008). They showed that naming an instance of an element category was quicker when an analogical or categorical judgment had previously been achieved when compared to a task of judgment of the presence of a relation within the two domains (i.e., judging if there was a relation between the words presented in columns). Naming of an instance of the same relational category as the ones used to construct the analogies was also quicker when people had to simply say if there was a relation between the words presented in columns or to judge if the four-word analogy was true than when participants were only asked if between-domain elements were of the same category.

Gentner & Kurtz (2006b) showed that not only element categories but also relational categories were important in adults' analogical reasoning. Their participants accepted analogies as valid even though relational concepts the two domains carried were not strictly overlapping, but carried commonalities. They were also prone to judge these analogies as highly similar.

These experiments argue in favor of the activation of the categories that are common to the objects and relations put into correspondence in the two domains during analogical reasoning. This category activation might also help to guide the mapping process, which is coherent with the previously reviewed literature about distance between domains: distant domains might elicit categories that are hierarchically more distant to the basic level of categorization.

Reasoning development

A logical prediction from the hypothesis exposed by Green and colleagues (Green et al., 2008; Green et al., 2006) would be that, if children's mapping is affected by category relations between the source and the target domain in the same way as adults', answer options that are categorical matches to the B term would be likely to be selected by children. To our knowledge, this prediction has not been tested yet. Nevertheless, there is empirical evidence that categories influence children's analogical reasoning in other ways.

Goswami & Brown (1990) gave children of 4, 5 and 9 years of age the classical A:B::C:? task in a forced-choice manner. The solution alternatives were pictures of the same theme or the same category as C, and mere-appearance matches, in addition to the analogical solution. Overall children performed well on the task, and younger children more likely preferred thematic choices over the other possibilities when they made errors. This might be interpreted as a sign of a focus on relational information, even though not the precise relation that is similar to the one that is between A and B. Hence, children seem to be first influenced by the commonality of thematic category between C and the potential solution.

Purser, Thomas, Snoxall, & Mareschal (2009) explored how the development of categorization influenced metaphor judgment in children. It is known that categorization development starts at the basic level and then continues to the subordinate level (Mervis & Crisafi, 1982). They thus hypothesized that this categorization level would influence the types of inferences drown by children from metaphorical statements. To do this they asked children of 4-5, 7-8, and 9-10 years of age to judge of the validity of an metaphor in the story presented. For example, if the main character found an apple and said "Let's play with this apple. This apple is a ball.", children had to rate on a 1-5 scale how valid the metaphor of an apple being a ball was. Each metaphor was presented either with a basic level object (e.g., ball) or a subordinate level object (e.g., tennis ball). Ratings of basic level metaphors validity stayed constant across all age groups, but the validity of subordinate level metaphors increased with age, with younger children preferring basic level metaphors ad older preferring subordinate metaphors. In addition to this, the rates of subordinate justifications for subordinate level metaphor and basic level justifications for basic level metaphors also increased with age, when those of non metaphorical justifications and basic level justifications for subordinate metaphors decreased. As is evident in the classification of Gentner & Clement (1988), at least some metaphors meet the criterion and qualifies as proper analogies in the sense of a pure relational structure match. Thus, even though it was not tested in an analogical task yet, it might be that children are guided in their ability to draw and understand analogies, by the evolving structure of their conceptual system into several levels of categories.

The organization of semantic knowledge into categories seems to be an influent factor on both adults and children's analogical reasoning. Thus, the development of the conceptual system in children is likely to have an impact on the development of analogical reasoning. We will refer back to this idea when exposing the knowledge-based account of analogical reasoning development.

Language

Language is by definition an organization of concepts. Thus, it seems natural that this symbolic description of the world could affect the way we reason about it. This topic, especially relational language, generated a great amount of studies in analogical reasoning literature.

Mature reasoning

The functional role of words in analogical reasoning processing has been explored by Son, Doumas, & Goldstone (2010). They investigated the reason why words promote relational learning and reasoning, hypothesizing that they either were an invitation to compare and extract/represent the structure of different instances of the same pattern or that words carried semantics about structural aspects. To test these hypotheses they contrasted structural alignment of the stories (matches between the values of the target and distracters in the source and target stories, e.g., healthy athletes in the source corresponded to sweet melons in the target, and unhealthy athletes to bitter melons) used to teach Signal Detection Theory (SDT), and the coherence of the semantics of the relational words and the source story matches to these words (i.e., the "target" and "distractor" of the SDT have positive or negative values, e.g., the healthy athletes are the "target" (congruent case) or unhealthy athletes are the target (incongruent case)). Transfer was more effective when words were used in conjunction with alignable structures (i.e., stories with targets being consistent in their valence (positive or negative) in both source and target domains). However transfer did not happen or was negative (in the case of two structurally non alignable stories) when relational words were inconsistent with the valence of the source story (i.e., targets being associated with unhealthy and distracter with healthy).

This supports the view that the positive relational label effect is due to words' ability to be used as handles for alignable situations and not from their semantic overlap with situations. Thus words might be considered as objects standing for more complex relational structures in cognitive computations, as Clark (1998) hypothesized. Hence words might be a way of chunking information, coherent with Halford, Wilson, & Phillips's (1998) view of how people's working memory's efficiency is increased.

Reasoning development

The positive effect of words on analogical reasoning is not restricted to adults, and several studies show similar effect on children.

Rattermann & Gentner (Rattermann, Gentner, & DeLoache, 1990; Rattermann & Gentner, 1998a; Experiment 2 & 3) showed the effect of relational labels on 3- and 4-year-olds' performance in a simple mapping task. In this task children had to take into account the size relations within the source and target domains to find which object in the latter was the equivalent to the one pointed to in the former. Using relational labels (i.e., Daddy, Mommy and Baby; Rattermann et al., 1990; Rattermann & Gentner, 1998a; Experiment 2), 3-year-olds had higher performances than when not using them, and even outperformed 4-year-olds who were not administered the label condition. In their third experiment, Rattermann & Gentner (1998a) found similar results using the Daddy/Mommy/Baby labels, and a Big/Little/Tiny labeling of the different objects. This effect was stable in time: the 3-year-olds tested 1 to 4 month after the training with the label still showed better accuracy than children tested in the condition without labels.

Kotovsky & Gentner (1996, Experiment 3) tested the effect of labeling on their triad mapping task. Children were first trained to use the "even" label for symmetrical triads and tested in their ability to categorize the pictures as even or not, and then tested on Cross-Dimension trials (i.e., in which they had to map the size relations onto color relations between the objects composing the triads). Four-year-olds who perform well in the categorization task also tend to perform well in the analogical reasoning task, which was confirmed by a χ^2 analysis on over- and below-average children in the two tasks.

Loewenstein & Gentner (2005) found similar results of labeling in 3-, 4-, and 5-year-old children in spatial mapping tasks, with the effect on the two older groups' performance only being present with more difficult tasks. Exploring further the effects of the semantics of the words they used (either "top/middle/bottom", which conveys a more integrated set of relations, or "on/in/under" which conveys only a set of first order relations), they found that 4-year-olds benefitted more from the more integrated labels. This effect of labeling was also robust in time: 3-year-olds tested two days after the first test session were still better in the label condition than in the control condition.

However the effect of language on analogical reasoning is not specific to the oral language and the auditory modality. Evidence by Bandurski & Galkowski (2004) comparing deaf children early exposed to sign language and hearing children in their analogical reasoning ability on verbal, numerical and geometrical analogy tasks. Children early exposed to sign language had performances equivalent to those raised with verbal language from birth. Convergent evidence come from Gentner, Ozyürek, Gürcanli, & Goldin-Meadow (2013) who tested hearing children and deaf children who were not raised practicing typical sign language and invented their own (homesigners). The authors found that homesigners conveyed less spatial relations than hearing children, and, when tested in a spatial mapping task like the one used by Loewenstein & Gentner (2005) in which one had to find on which level of a shelf an object was hidden on the basis of the location of an object on another shelf, homesigners had significantly lower scores than hearing children.

Words thus seem to allow children, like adults, to encode and focus on the relational information, giving a unity to a relational structure, and compute it as a single object. It also appears that this effect of chunking a whole set of relations into a single word is not limited to verbal language, but generalizes to any stable kind of description (e.g., official sign language and homesigning).

IV.c. Working memory and executive control's involvement in analogical reasoning

Working memory can be seen as the workspace where information is stored and operated on during the solution of a task. The most influential model of working memory is Baddeley's (1983) model, which describe it as different sub-systems: the visuo-spatial sketchpad involved in the retention of spatially organized information, the phonological loop which serves as a verbal information storage, and the executive control which is the system that operates transformations on the information stored. Evidence exists that the executive control component of working memory is closely related to what is usually referred as executive functions (Chevalier, 2010; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Executive functions are used by the subject to regulate his thoughts and actions to achieve more or less distant goals. The different executive functions usually referred to are inhibition (either of information in working memory or behavioral inhibition), cognitive flexibility (the ability to shift the attentional focus from one description to another), and working memory refreshing (Chevalier, 2010). However the clear classification of executive functions is still under debate. Nevertheless a consensus seems to have been reached about executive functions being limited, and their development being late in life in comparison to sensory-motor functions, changes still being observed through adolescence and early adulthood (Diamond, 2013; Gathercole, Pickering, Arambel-Liu, & Wearing, 2004).

Working memory capacity, the phonological loop and the visuo-spatial scratch-pad

First we will explore the literature about the involvement of working memory functioning in analogical reasoning. Working memory can be seen as the "place" where representations of the two domains compared will be stored and where operations such as the mapping of one domain on the other and the transfer of information from one domain to the other will be operated.

Mature reasoning

(Waltz, Lau, Grewal, & Holyoak, 2000) studied the link between working memory capacity and a scene analogy task. In their first experiment, they asked their participants to hold a seven digit series while finding the objects that corresponded to the objects of the first scene in the second. They found a negative effect of working memory load on the ability of their participants to perform this task. Their second experiment tried to disambiguate the relative involvement of the central executive and the phonological loop. To interfere with the mapping task, they used a random digit generation task (assumed to require the executive control subsystem of working memory) in one condition and a simple syllable repetition task (requiring only the phonological loop) in another. Both subsystems' overload had an equal negative effect on the mapping task. Thus, mapping a domain on another one might require both the phonological loop and the executive components of working memory. In both of these experiments, they also found that working memory was more loaded by a relational mapping task than an object matching task, the former being replaced by the latter in conditions of addition of a load on working memory.

Morrison, Holyoak, & Truong (2001) also explored the link between the different slave systems of working memory (i.e., the visuo-spatial scratch-pad and the phonological loop) and analogical reasoning in visual and verbal analogies. Articulatory suppression specifically affected participants' performance in the verbal analogy task, when interference with the maintenance of visual information in working memory by asking participants to point to four dots in a clockwise order selectively disrupted their performance in the visual analogical reasoning task. Asking participants to generate a random number between 0 and 9 disrupted their performance in both task. These results suggest a differential recruitment of working memory subsystems depending on the modality of the analogical task. The effect of generating a random number on both task was interpreted as this task tapping in the same working memory resources as the analogical process per se, i.e. the maintenance of relations between the numbers already given (their order) to generate new numbers.

Convergent evidence was found by Tohill, Holyoak, & Angeles (2000), basing their research on the fact that induced anxiety narrows working memory capacity (Eysenck, 1979), thus predicting more object matches and less relational matches in a mapping task when state anxiety is induced than when it is not. This prediction was confirmed by empirical data, even when participants were asked to explicitly find relational matches. This result is reinforced by a study by Chuderski (2013) showing that when speeded up, participants' working memory variance explains most of the variance between participants' performance in two relational reasoning task (i.e., Raven Progressive Matrices and A:B::C:? analogies).

An interesting link which has been made in the theory of Halford, Wilson, & Phillips (1998) between relational complexity and working memory is that people can handle more relational information in working memory by chunking meaningful structures into single handles (a function that can be achieved by words, see above). This nevertheless leads to the inaccessibility of the details of this information. Kubose, Holyoak, & Hummel (2002) used this theoretical point to construct a series of experiments exploring further the link between mapping and working memory. In their view, mapping is incremental, directional, and thus is affected by factors affecting the order of mapping (i.e., the likelihood of chunking propositions in a phase set, the features of the groupings that are made, and the selection of an analog as the driver of the analogy) due to working memory capacity limits. Their first experiment showed the effect of a causal content in the analogs compared (this causal content supposed to ease chunking relational structures in working memory) in contrast of a condition without causal structure. Both conditions had a hint to group sentences (i.e., a box surrounding them), but not the third, control condition. Participants' mapping was more accurate in the "causal grouping" condition than in the "non causal grouping" condition. The control condition's scores were higher than in the "non causal grouping" condition (where sentences not linked causally, hence not easily chunked, were grouped in the box) thus showing facilitation due to the grouping of only causally consistent sentences in working memory, in accordance with Halford et al.'s (1998) theory. The second experiment reproduced these results with semantically richer analogs and contexts. It also showed that grouping causally linked sentences facilitates inference in the target by putting higher constraints on the matching between roles in source and target domains. The third experiment explored the asymmetry in the mapping process due to a higher-level causal structure of the driver (explained by constraints on working memory capacity). Indeed, as the LISA theory argues (see subsection III.b., this chapter), the limit in working memory capacity imposes directionality in the mapping process from a driver to a recipient which only responds to the activations in the driver. Thus, a better structured (i.e., causally structured) source might be more beneficial for mapping than a better structured target. Data actually showed that mapping was positively affected by the presence of a causal structure in the source, but not in the target and was replicated in the fourth experiment with rich semantic stories.

Convergent data of working memory capacity limiting adults' analogical reasoning comes from Cho, Holyoak, & Cannon (2007) who showed that the relational complexity (i.e., the number of relations to be taken into account simultaneously to solve the problem) of the trials affected participants reaction times and accuracy in a people pieces analogy task (Sternberg, 1977). Similar results were obtained in geometrical analogies (Mulholland, Pellegrino, & Glaser, 1980).

Working memory capacity seems to limit by the number of relations, the number of their arguments, and the possibility to chunk relations, the relational structures that can be handled and compared by adults while drawing analogical comparisons.

Reasoning development

Working memory capacity increases across development (Gathercole et al., 2004). Early indirect evidence suggested that working memory was an inherent limit to analogical reasoning in children (Sternberg & Nigro, 1980). A study by Richland, Morrison, & Holyoak (2006) explored directly the link between the limitations and development of working memory in children and their ability to reason by analogy. They explored this link using Halford et al.'s (1998) framework of relational complexity (i.e., the dimensionality and number of relations that are relevant at the same time for the solution of a problem). They tested 3-to-4-, 6-to-7-, 9-to-11-, and 13-to-14-year-olds in a scene analogy task, in which children had to find an entity that was the same part of the pattern in the bottom picture as the entity pointed to in the top picture's pattern. The structures of the patterns in terms of relations were identical in both pictures. They varied the patterns in terms of the number of relations. For example, in one condition, children saw a mouse chased by a cat and a girl chased by a boy, and in the other, a dog chasing a cat which itself chased a mouse, and a mother chasing the boy who chased the girl. The number of relations affected children's ability to answer correctly, especially in the two younger age groups, which suggests a developmental trend toward an ability to handle a greater number of relations while reasoning by analogy.

Different amounts of information seem to overload adults' and children's working memory capacity when reasoning by analogy. This is consistent with the view of working memory capacity and chunking strategies developing from childhood to adulthood.

Executive control component of working memory and executive functions

As described above, a link was found between the executive control component of working memory and analogical reasoning (Waltz et al., 2000), thus showing the implication of executive functions in this ability. One commonly acknowledged executive function is the inhibition of information that has entered the working memory or might enter it. The following subpart describes evidence of the involvement of this particular executive function in analogy-making.

Mature reasoning

Chuderski & Chuderska (2007) found correlations between participants' performance on a geometrical analogy task with a large set of executive function measuring tasks (i.e., assessing updating of the information in working memory, inhibition, task switching, dual-tasking, changing goals, and interference resolution). The highest correlation values were found with the goal monitoring and inhibition tasks. A Confirmatory Factor Analysis leads to a very good fit to the data with only taking into account these two executive factors.

In a follow-up study, Chuderski & Chuderska (2009) found a correlation between scores in a n-back task and in the same geometrical analogy task. They argued this correlation was mainly due to the inhibition component of working memory rather than its capacity (both assessed by the n-back task) because participants with low and high rates of correct answers in the analogy task differed mainly in their number of false alarm rates in the n-back task in a forced choice condition, and because the working memory span was not predictive of analogical transfer performance.

Cho et al.'s (2007) study, using people pieces visual analogies (see above), showed that participants reaction time was affected by the number of interfering dimensions (i.e., that had not to be taken into account) and that these two factors (i.e., the number of dimensions to take into account, and the number of dimensions to inhibit) interacted.

Another study using people pieces analogies, by Viskontas, Morrison, Holyoak, Hummel, & Knowlton (2004), assessed young, middle-age, and old adults in their analogical reasoning abilities. They similarly varied the number of relations and of interfering dimensions and found negative effects of age, level of complexity and level of interference on accuracy and reaction times. This suggests a decay in the ability to solve analogical reasoning problems linked to working memory capacity and inhibition of interfering information in aging and thus, that these process are involved in analogical reasoning.

Evidence that cognitive flexibility is also involved in adults' analogical reasoning come from Barnes & Whitely (1981). In their study, they constructed semantically ill-structured A:B::C:? forced-choice problems by exchanging the B and C terms of in well-structured A:B::C:? problems (e.g., *deep:shallow::cheap: a) costly, b) wide* to *deep:cheap::shallow: a) costly, b) wide*), but also perceptually ill-structured problems (i.e., ?:C::B:A structures instead of A:B::C:? structures). The last class of problems was produced by using both transformations at the same time. Both types of transformations negatively affected participants' reaction times without interacting, but accuracy was only affected by the semantically ill-structured problems. This suggests that when problems are ill-structured, an additional, restructuring process is necessary to find the solution of the problem. The restructuration of the process in a well-structured problem leads to a novel representation, and has a cognitive cost (materialized in the increase in reaction time and decrease of accuracy) and is most probably through cognitive flexibility which underlies the ability to re-represent the problem space into a new, meaningful way leading to its solution. This study is the only one to our knowledge to explore the link between cognitive flexibility and analogical reasoning in a causal, non-correlative way.

All these studies indicate that executive functioning is part and parcel of normal analogical reasoning, and that altering this functioning logically impairs the ability of adults to draw analogies efficiently.

Reasoning development

Developmental studies are critical in the study of the link between executive functions and analogical reasoning, as executive functions are known to have a late development

(Diamond, 2013). Thus, if these functions are involved in analogy-making, it is likely that researchers will observe qualitative differences in the way analogical reasoning operations are performed during development.

Early evidence of differences in inhibition of information between children with high and low performance on analogical reasoning tasks comes from Marr & Sternberg (1986). They tested 11- 12- and 13-year-olds in a verbal, forced-choice analogical task. These children were divided into two groups: gifted (IQ above average and excellent performances at school) and non-gifted (average IQ and performances at school). Gifted children allocated less time to irrelevant information when compared to non-gifted children, suggesting better inhibition of the irrelevant information in the former than in the latter.

Hosenfeld, van der Maas, & van den Boom (1997) tested children aged 6 and 7 in a geometrical analogy task in repeated sessions and tracked their developmental trajectories. The relational complexity of the trials (i.e., the number of differences to take into account to succeed in solving the analogy) was varied between trials. Even though all children improved their performances across sessions, they observed different trajectories of development: non-analogical reasoners who consistently solved the trials by non analogical solutions, analogical reasoners who solved most of the trials by analogy even in early stages of the experiment, and transitional reasoners who started as non-analogical reasoners and ended as analogical reasoners. Doumas, Morrison, & Richland (2009) used the LISA model to simulate these results. They achieved the modeling of the three different groups by varying the inhibition component of the working memory in LISA. This suggests that the differences observed in the ability to solve analogical reasoning tasks by children are explained by this component of working memory.

The study reported in the working memory section by Richland et al. (2006) also explored the ability of children to inhibit an object match distractor. To do this, they varied the presence or absence (in which case it was replaced by a perceptually unrelated object) of such a distractor. They found an interaction between the condition (presence or absence of the distractor) and age showing that younger children (3-to-4- and 6-to-7-year-olds) were more disturbed by the presence of an object perceptually similar to the one pointed at in the top scene than older children (9-to-11 and 13-to-14 years age). This suggests that the development of the inhibition component of executive functions also plays a role in the development of analogy-making abilities.

Simms & Gentner (2009) used a similar scene analogy task to test children aged 3 and 5 in three different conditions: a condition in which there was no distractor, another in which the distractor was external to the target relation, and a third one in which the distractor was internal to the relation of interest (i.e., cross-mapped). They tested children with relational or neutral language. Without relational language, children correctly solved the problems in most of the cases when there was no distractor. However in the two other cases, they had significantly lower performances. However this effect of distractors was counteracted by the use language by the experimenter of relational (e.g., “Do you see this one that’s *towing*?” when a truck towing a car, and a car towing a boat on a trailer were presented). They performed at the same level in all three conditions. In addition to this, 5-year-olds were less affected than the 3-year-olds by the presence of distractors. In a second experiment, the authors explored the link between children's ability in the same analogical task and in an inhibition task (i.e., the day night task, in which children have to say day when the experimenter points to night, and vice versa). They found a significant negative correlation between the two measures in 3-year-olds, no correlation in 4-year-olds, and a positive correlation in 5-year-olds, suggesting that the relation between inhibition and analogical reasoning ability evolves through time. However the results in the younger group is mitigated by their implementation of strategies not directly related to the goal of the Day-Night task (e.g., alternating between saying "day" and "night" without taking into account the pictures), potentially blurring these results. A similar, positive correlation was obtained between inhibition measurement in a day night task and analogical ability measured in a semantic A:B::C:? task in 4- and 5-year-olds (Thibaut, French, Vezneva, Gérard, & Glady, 2011). The account of children's failure in semantic A:B::C:? task in terms of inhibitory control maturation is consistent with eye-movement study of children in this task showing that they looked longer at distractors than adults (Thibaut, French, Missault, et al., 2011).

Convergent results about the link between inhibition and analogical reasoning, and especially the interactive nature between inhibition and the structure of semantic knowledge of children comes from Thibaut, French, & Vezneva (2009, 2010). They assessed children's (3-to-4 years) ability to solve semantic A:B::C:? problems and varied the number of distractors (either 1 or 3) and the association strength (strong or weak association in long term memory between A and B, and C and the solution and C and the distractor, resulting in all strong or all weak trials). They found a significant interaction between the strength of association and the number of distractors associated to C: in trials with strongly associated pairs, children performed well whatever the number of distractors. However in the weak association strength trials, the performance dropped in the trials with three distractors. This suggests that young children's ability to infer relations when solving analogical problems is supported by the association strength. In weak trials, however they can't count on this support, and thus the inference of the relations between the different terms of the analogy is more cognitively demanding which causes greater interference in the solution of the task when there is a greater number of potential relations (i.e., three related-to-C distractors) to inhibit. This is suggestive of the dependence of executive functions, inhibition in this precise case, on their substrate (i.e., semantic, conceptual content represented in working memory).

In addition to the manipulation of factors in relation to executive functions in analogical reasoning task, executive functions at an early age is also a good predictor of future analogical reasoning development, as is their knowledge about the world (Richland & Burchinal, 2012). In this study, they analyzed data about children, collected in early elementary school, assessed in their ability along various cognitive dimensions (i.e., executive functions, sustained attention, short term memory, and vocabulary knowledge), and then tested in their fifteenth year in a verbal analogy task. Significant correlations were found between executive function as measured by Tower of Hanoi test, and the more specific inhibition component measured by the Day-Night Task and results in verbal analogies, as well as vocabulary knowledge.

Another study in favor of an interaction between knowledge and executive function is a study by Richland, Chan, Morrison, & Au (2010). They compared Chinese and American children in the previously described scene analogy task. The basic assumption of this study was that Chinese cultural environment was more oriented toward relations than American cultural environment, thus favoring their knowledge. Thus cultural conventions might facilitate or slow down analogical reasoning development by this means of cultural focus. Children from the two different countries did not differ in their ability to solve problems with only one relation to be taken into account. However, when attention to two simultaneous relations was required, Chinese children outperformed their American counterparts. These different patterns were also simulated using the LISA model by varying the inhibition component of working memory (Doumas, Morrison, & Richland, 2010; Morrison, Doumas, & Richland, 2011). Convergent results were obtained by testing Japanese and American children (4 years age) in a triad matching task using sparse and rich objects (Kuwabara & Smith, 2012). Children from the United States of America performed as well as Japanese children when the objects were sparsely detailed. However with the rich objects, American children performed poorly in comparison to their Japanese counterparts. On the contrary children from America had shorter reaction times in an object search task, which is predicted by the theoretical point raised above about intercultural differences.

In this section we have introduced the discussion of the role that executive functions could play in normal analogical reasoning and its development. However, as noted by Chevalier (2010), executive functions intrinsically depend on the substratum they work on, and thus, it is likely that both knowledge about the world and executive functions interact in close accordance when reasoning by analogy. Thus the two previous sections are not mutually exclusive in their account of how analogical reasoning works and develops, and would better be considered as two sides of the same coin.

IV.d. Planning, strategies and metacognitive aspects of analogical reasoning

Planning, strategy implementation and metacognitive aspects are fundamentally linked to executive functions, and are involved in strategy use: they permit to act on the substratum of the task to pursue goals which are ordered in time. Thus differences in strategies are likely to appear with the maturation of executive functions. Planning and goal management are also tightly related to subjects' understanding of the task and its constraints on the solution, because this understanding will lead to a strategy rather than another.

Mature reasoning

One of the first studies that investigated the different strategies used to solve analogical problems is the study of Whitely & Barnes (1979) which used protocol analysis in participants' requests for information when solving verbal A:B::C:? problems using unreal animals. Because the labels did not correspond to any known animal, participants had to request information from the experimenter to correctly solve the analogies. The full set of animals' properties was given to the participants at the same time. Overall Whitely & Barnes found an important between-subject variability in the strategies: 18% solved the problem directly after encoding, 23% made one confirmation step before answering, 45% requested information about the whole stem (i.e., A, B and C) before searching for a solution, only 10% asked more information about C before searching for a solution. Other strategies were only marginally observed. This suggests individual differences between participants in their ability to deal with the amount of information given to them (supported by executive functions and working memory capacity) in the task, and to articulate it in a meaningful analogy, leading to different strategies.

Bethell-Fox, Lohman, & Snow (1984) were the first to address the question of participants' strategies in analogical reasoning recording eye-movements data. They hypothesized a strategy shift within subjects in simple and difficult geometrical A:B::C:? trials, and a difference of strategy between high fluid intelligence and low fluid intelligence participants. They found evidence for two different strategies: constructive matching, used in easier problems, and more widely by participants with high fluid intelligence, and response elimination, used more in harder problems and by participants with low fluid intelligence. Constructive matching consists in constructing a full model for the answer on the basis of the first three terms of the analogy, and response elimination consists in eliminating the answers that do not fit on the basis of partial evidence from the stem of the analogy.

Mulholland et al. (1980) also explored their participants' strategies in a geometrical analogy judgment task. In this task, participants first encoded exhaustively the difference between A and B, then generated the rules for changing A into B, which was followed by a phase of encoding C and D, mapping of the attributes of A:B on C and D, and comparing the different operations transforming C into D to those stored in working memory between A and B. A answer is given if one of the operations is not present or is not the same as in A and B or if all inferred operations correspond to those between A and B. This strategy, different from the one postulated by Sternberg (1977; see above) and Whitely & Barnes (1979), is most probably the resultant of the task constraints that differ from analogical judgment (in which a D term is given and has to be evaluated) to analogical problem solving (in which the D term has to be found between different solution options).

These studies show that adults can adapt their strategies in response to the limitations of their executive functions and working memory. However these different strategies lead to correct answer most of the time, which suggests that they understand correctly the constraints on the solution of the task, and that these strategies are adapted to these constraints.

Reasoning development

However, children's knowledge about the constraints of the task and their own limitations, and their ability to manage the different goals of analogical reasoning tasks seem to be limited at first, and to develop over the years, as the following review demonstrates.

One of the earliest positions about children's strategies development in analogical reasoning task is a shift from associative to analogical responding due to maturation processes (Piaget et al., 1977) and the extent to which children used associative responding was negatively correlated with their IQ and achievement (Achenbach, 1970a, 1970b), even in the long run (Achenbach, 1971). Associative errors were also negatively correlated with working memory capacity (measured by a simple digit span task) and semantic flexibility (measured as the ability to find in a list of words the different meanings of a word when in the context of words coherent with only one meaning) in 10-to-11-year-olds (Tirre, 1983).

Sternberg & Nigro (1980) observed in their children (9-, 12-, 15-, and 18-year-olds) an increase in consistency in the use of strategies across trial difficulties, and found differences in the models accounting for children's performances with age. First, children's (9 and 12-year-olds) reasoning tend to be guided by the association strength between the last word of the stem of the analogical problem and the first word of the solution option, suggesting an incomplete form of analogical reasoning, with an incomplete encoding of the analogical problems (possibly linked to a limitation in working memory). Older children and adults (15 and 18-year-olds) rely more exclusively on their reasoning abilities to relate the analogical problem parts and tend to have exhaustive processes, suggesting less limitation from working memory capacity in their strategy. Similar reliance on association was observed in older children and adults when learning novel domains (Alexander, Murphy, & Kulikowich, 1998).

Even though most of the materials in the preceding studies were semantic, a similar trend toward using associated matches were found in geometrical analogies (Alexander, Willson, White, & Fuqua, 1987). In this study, children (4-to-5 years of age) who did not solve the problems by analogy relied on a hierarchical set of rules to choose their answer: they used the similarity (which could be interpreted as perceptual association) between the potential answers and the C terms of the problems. Thus, non analogical reasoners tended to choose the exact match with C, or, if absent from the solution set, an item that was identical to the greatest number of dimensions possible, instead of the correct answer.

The same bimodality of responding (i.e., similarity or analogical matching) between the age of 5 and 11 has been found in an analysis of several sets of data using geometrical analogies varying the relational complexity of the transformation from A to B, and was interpreted as an indicator of a developmental discontinuity in the way children apprehend analogical problem solving (Hosenfeld, van der Maas, & van den Boom, 1997b). This transition, indicated by bimodality between subjects of different age, was also shown in longitudinal data (Hosenfeld et al., 1997a). Six-to-eight-year-old children were tested in the same geometrical analogy task as in Hosenfeld et al. (1997b) with eight sessions on a six-month period. They identified four indicators of transition between two modes of responding: bimodality (i.e., two different strategies of responding between subjects), sudden jump (i.e., sudden change of responding within subject), anomalous variance (i.e., increase in variance due to a conflict between the two modes of responding near the transition point), and critical slowing down (i.e., increase in reaction time due to the conflicting strategies near the transition point). Convergent findings indicating a developmental transition around the same age was found in simple 2x2 Raven Progressive Matrices task which is another test of relational reasoning close to the A:B::C:? task (Siegler & Svetina, 2002).

Interestingly, a similar trend from associative to analogical reasoning has been observed in adolescents in more complex, third order analogies (i.e., analogies between analogies; (Sternberg & Downing, 1982). Samples of 13-, 16-, and 18-year-olds were tested in a meta-analogical judgment task. They were presented with two analogies and asked to rate on a 1-to-9 scale how analogically related were these analogies (e.g., how analogically related were sand:beach::star:galaxy and water:ocean::air:sky). The authors also showed that the ability to map one domain on the other (i.e., to observe the similarity between the relations in the two domains) was the last to develop in this meta-analogy task, as it was in younger children in more simple analogy tasks (Sternberg & Rifkin, 1979). This development of the ability to map analogies one on the other and thus extract more complex schemas could lead to meta-analogical skills (i.e., the ability to draw analogies about analogies, Burns, 1996). The observation of the same development from associative to analogical reasoning at two different ages with problems of increasing complexity suggests that the ability to make chunks of increasing information is crucial for the ability to judge and use similarity between domains.

Hence, during development, an increase in children's ability to take into account the main goal of analogical reasoning (i.e., to compare the two domains on the basis of their similarity) and in their understanding of how it is implemented could explain the decrease in associative responding. Children's comprehension of the task itself and its constraints was shown to be decisive in the ability to solve analogical problems (Goswami et al., 1998). In this study, children aged 4 to 5 were tested in A:B::C:? problems using causal transformations between both pairs of pictures, and controlled in their knowledge of the relations used. They varied the number of relations (either one or two) and the order of the different tasks (single relation A:B::C:? task, causal reasoning control task, double relation A:B::C:? task). They found a significant effect of the number of relations, mostly due to the poor performances in the double relation analogical reasoning task when it was the first task. However, children presented first with the single analogy task did not have different performances between the single and double relation A:B::C:? task. These results can be explained by the fact that a first exposure to the task with simple relations helps them understand the constraints put on responding in the A:B::C:? task, even in more complex trials. Therefore, young children's associative responding might be explained by their inability to understand the structure of the task itself or to keep it active, especially with difficult stimuli. Training them with a simpler task might consolidate their representation of the constraints on the solution of the problems. These results suggest also that the attentional focus on relation observed in children who are trained with a progressive alignment procedure might attend more to relational features because of a better understanding of the task constraints.

Other evidence showing children's poor understanding of the task constraints have been gathered (Cheshire, Ball, & Lewis, 2005). In this study, children (aged 6 to 7) were tested over several sessions in different conditions (control, practice only, feedback, self-explanation of the answer, and self-explanation and feedback) in a simple 2x2 Raven Progressive Matrices test. They showed that children both benefitted from the self-explanation and the feedback condition. However, children in the self-explanation and feedback benefited from an additive effect between those two helps. The feedback condition was argued to have an effect on children's representation of the constraints of the task on the adequate solution, when the self-explanation condition was interpreted as helping children maintaining attention toward the goals of the task. This explanation is plausible as children have been shown to demonstrate goal neglect in complex tasks (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008a; Marcovitch et al., 2010). Thus, children's failure in analogical reasoning task could be due at least in part to a failure to represent correctly the task's goals and keep them active throughout their search.

Many studies involved children's training in analogical reasoning task. Alexander and colleagues (Alexander et al., 1989; Alexander, Haensly, Crimmins-Jeanes, & White, 1986; White & Alexander, 1986; see also Tunteler, Pronk, & Resing, 2008; Stevenson, Heiser, & M. Resing, 2013) trained children in the different cognitive components of analogical reasoning problems (i.e., encoding, inference, mapping, and application; Sternberg, 1977). They found improvement in the children observed both in verbal and geometrical A:B::C:? tasks, suggesting that a better understanding of the tasks' constraints and goals positively affects children's performance.

Clues indicating a possible goal neglect in children were observed in children's eye-movements gathered while they were solving a semantic A:B::C:? task (Thibaut, French, Missault, et al., 2011). The authors compared children's (5- and 8-year-olds), adolescents' (14-year-olds) and adults' visual strategies and found that both children's groups were less likely to gather information from A and B than adolescents and adults. This indicates a potential neglect of a major subgoal of the task (i.e., finding the AB relation in order to compare it to the possible solution's relations to C), which might cause at the basis of children's associative strategy: they might focus on the goal of the task that is the most emphasized (i.e., finding something that goes with C) without taking into account the constraint that this solution should be linked to C *in the same way as B is linked to A*.

V. Goals and Hypotheses of the Present Dissertation

The general goal of this dissertation was to investigate the roles of executive functions and goal management in analogical reasoning in different tasks usually used to assess this ability. We have reviewed evidence suggesting that executive functions are involved in analogical reasoning ability in adults: dual tasking involving a task tapping on the executive control component of working memory interferes with analogical reasoning (Waltz et al., 2000), there is a correlation between executive function abilities and analogical reasoning abilities in adults (Chuderski & Chuderska, 2007, 2009), the number of interfering dimensions affects negatively reaction times in young and older adults (Cho et al., 2007; Viskontas et al., 2004), and participants are affected in their performance when they have to restructure the problems presented into a meaningful representation (Barnes & Whitely, 1981). Other evidence comes from developmental studies: high IQ children differ in the time spent on irrelevant information from average IQ children in the A:B::C:? task (Marr & Sternberg, 1986), children have difficulty inhibiting distractors while solving analogical problems (Richland et al., 2006; Simms & Gentner, 2009; Thibaut, French, Missault, et al., 2011; Thibaut et al., 2009, 2010a, 2010b), interindividual and intercultural differences are best modeled by varying the inhibition component of working memory in LISA (Doumas et al., 2009, 2010; Morrison et al., 2011), and executive functioning in childhood predicts accurately later analogical reasoning abilities (Richland & Burchinal, 2012) and inhibition is correlated with analogical performance in young children (Thibaut, French, Vezneva, et al., 2011). Ongoing goals also affect analogical reasoning were also reviewed: Different goals affect the result of the mapping process (Spellman & Holyoak, 1996), and the inability to keep active the "similarity between relations" goal of the task might explain children's failure in analogical reasoning tasks (Brown et al., 1986; Sternberg & Nigro, 1980; Sternberg & Rifkin, 1979; Thibaut, French, Missault, et al., 2011), training children on the constraints on the solution of the task and its goals help them have better performance (Alexander et al., 1989, 1986; Cheshire et al., 2005; Stevenson, Heiser, & M. Resing, 2013; Tunteler et al., 2008; White & Alexander, 1986). All these studies suggest that executive functions and goal management are part and parcel of mature analogical reasoning, and that the development of these abilities constraint the development of analogical reasoning. However, there are still gaps in our comprehension of how executive functions and goal management relate to analogical reasoning.

V.a. Visuals strategies in analogical reasoning

Studies of analogical reasoning using eye-tracking technologies are very limited in number. We reviewed in the previous section several experiments which used eye movements as a clue of information processing of participants. Bethell-Fox et al. (1984) showed that participants used different strategies in difficult and easy trials of a geometrical A:B::C:? task, depending on their cognitive resources. Gordon & Moser (2007) studied adult visual strategies in the Scene Analogy Task and showed that fixations were longer on the objects involved in a relation, and saccades were more frequent between a third object when it was also linked by a relation to the other two involved in the goal relation, than when it was not.

Thibaut, French, Missault, et al. (2011) showed that children were more focused on the C and the solution set than adults, especially at the beginning of the trials. Goals of the present dissertation were then to gain insight in the development of visuals strategies in the Scene Analogy Task. Comparison of children with adults in this task was not considered by Gordon & Moser (2007). Another goal was to compare these two different tasks in the visual strategies they elicited both in children and adults. These two different tasks testing analogical reasoning were never compared directly, and thus we do not know if they cause the same difficulties to and put the same constraints on participants' reasoning.

V.b. Influence of the goals of the task

Goal maintenance, the ability to keep a goal active during the solution of a task, is a necessary element of the elaboration of a strategy. This competence has been shown to develop during childhood (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008b; Marcovitch et al., 2010) but goal neglect still happens in adults and has been linked to working memory lapses (Duncan, Emslie, & Williams, 1996; Kane & Engle, 2003). As goals of the task influence analogical reasoning (Spellman & Holyoak, 1996) as well as the information gathered visually (Yarbus, 1967), one of the goals of this dissertation was to investigate the interaction between visual strategies and the goals of different tasks used to assess analogical reasoning. Indeed, some tasks are more focused on the similarity between the relations, like the A:B::C:? task, when other are more focused on the mapping of the elements of the two domains, like the scene analogy task (Richland et al., 2006). We hypothesized that the search for information in these tasks would be in accord to these instructions: participants would tend to relate more the elements of the two domains in the second than in the first task. Most of the models are not interested in the fine-grained level of eye movements and it is difficult to make predictions from them at this level as these models are not embedded in production systems and focus on the mapping process. However, LISA (Hummel & Holyoak, 1997), even though not precise about how information is encoded, and the path-mapping theory (Salvucci & Anderson, 2001) make predictions about the way participants would gather information: In the A:B::C:? task, they would first encode the relation between A and B, then encode the relations between C and the solution set one at a time until one meet the criterion of relational similarity and if different elements have relational similarity, compare the different relations to pick the one that is most similar to the relation between A and B. In the scene analogy task, they would also encode the relational structure of the source domain at first, and then encode the structure of the target. However, as the goal is to find the objects that are similar in their role in the relations, once the structure is extracted and the goal object in the source defined, they would try to relate it with the goal object in the target domain. Thus, an important prediction of the path-mapping theory (Salvucci & Anderson, 2001) is that the comparison between the two domains in term of mapping is not exhaustive and that when the main goal is achieved, the participant will answer without trying to relate other elements of the domains, which is at odds with other mapping theories and models which map the entire systems one on the other. This prediction would not be made by LISA or other theories presented in section III.b.

Another prediction from the view that goal affects deeply the analogical reasoning task is that, if there is an element in the target domain of the A:B::C:? task that has a relation to C that is exactly the same as B has to A, but that the mapping of the elements is inversed between the two domains, as the goal is to find a similar relation, participants would neglect to check the mapping between the elements of the domains compared. This would be predicted by ACME as the goal of the task is materialized by a bias on certain types of match: here it could be modeled by a strong bias on the correspondences between relations, which would lead to mapping errors at the level of elements. This could also be predicted by the path-mapping theory by modifying the goal structure of the task to allow mapping between relations uniquely and to trigger a response on the basis of the relational information only. However, other models do not take goals into account, and thus would not predict these results.

V.c. Children's goal management in the different tasks

As it has been shown that goal maintenance is harder for young children (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008b; Marcovitch et al., 2010), we also wanted to test children in A:B::C:? and scene analogy tasks similar to those used with adults. Eye-tracking methodology has proven beneficial to study this kind of issues in analogical reasoning: it has been shown that children did not attend to the A and B pictures to the same extent as adults in an A:B::C:? task (Thibaut, French, Missault, et al., 2011). We thus expected to find similar differences in the Scene analogy task. It has been shown that children's failure in this task was due to relational errors which, we believe, are due to the neglect of one goal of the task:

comparing the roles of the elements and maintaining them active for comparison. We hypothesized children would only focus on the relational similarity between the two domains without aligning the elements in terms of roles, and thus would not exhibit the same visual strategies than adults who would explicitly align the elements. The models of development do not say much about the importance of the ability of children to maintain goals while reasoning by analogy. Nonetheless Goswami's relational primacy account (Goswami, 1991, 1992) states that qualitative differences in analogical reasoning might appear through development, because of a better comprehension of the constraints on the solution and metacognitive processes, for instance. Even though not specific on which aspects are engaged in analogical reasoning, the ability to monitor goal achievement during the task can be seen as one (Flavell, 1979). Thus, monitoring goals would require goals to be maintained in order to evaluate their achievement. Strategic aspects are also envisaged by Gentner & Rattermann (1991) in their relational shift theory, and, as goals need space in working memory to be kept active, which could interfere with the representation of the relational structures of the domains, it can also be related to working memory explanations of development (Halford et al., 1998; Richland et al., 2006).

V.d. Involvement of executive functions in analogical reasoning

Executive functions are crucial in analogical reasoning. The search space view of analogical reasoning (Thibaut et al., 2010b) which sets the framework of the work presented here states that solving an analogical problem involves navigating through a space of possibilities formed by the subject from the semantics of the problems. Executive functions are central in this view, as they are the cognitive functions which permit to navigate through this search space efficiently and to carry out the strategy chosen by the subject.

Thus, we studied the dependence of analogical reasoning on executive functions. It was shown that visual strategies are linked to the complexity of the task in analogical reasoning in a geometrical task, and that complexity interacts with executive functions as they are implied in general intelligence (Bethell-Fox et al., 1984; Kane & Engle, 2003). However the complexity of a geometrical task is not comparable to the one of a verbal task: the geometrical complexity is clearly defined in terms of the number of transformations that have to be kept active in working memory, when the complexity of a verbal task is fuzzier, potentially involving more abstract relational concepts in difficult verbal analogical problems.

Verbal and geometrical tasks also differ in the saliency of the manipulated dimensions. However, as the format of the task is similar, with a forced choice setting, we expected to see a shift from a strategy of constructing the solution to a strategy of eliminating irrelevant responses, as was observed in previous studies (Bethell-Fox et al., 1984). However potential errors could not be attributed to larger working memory requirements in this study, as there was only one relation between the source and the target domains to keep active at a time. This shift of strategy would thus be due to executive functions' dependence on their substratum, as noted by Chevalier (2010). These results would not be predicted by current theories of mapping as they do not make differential predictions depending on the ability to clearly infer the relations involved of the task: the processes of mapping and transfer are executed on well defined relational structures by these models, as they are fed with rigid, handcrafted representations which do not allow other inferences than those given to them for the structures compared. It is impossible for them to change, for instance, the representation of a boy chasing a girl (i.e., mere facts), to a boy playing with a girl (i.e., giving a meaning to these facts). Such refining of the relations might appear in humans even though they do not know what is the relation used in the target, when using a response elimination strategy, that is not having enough constraints on .

The late development of executive functions should also affect how children execute their strategies and thus their visual patterns when solving the task. They should be more distracted by distractors, due to a difficulty to inhibit information relevant to some goals of the task but not to the entire set of constraints defining the analogous solution. Another aspect of the research presented in this dissertation on executive functions is the study of cognitive flexibility. Cognitive flexibility has not yet been explored to the same extent as inhibition in analogical reasoning literature, even if it is known that it is involved in adults' ability to solve analogical problems, especially when they are ill-structured (Barnes & Whitely, 1981). Studies involving children are well suited for the exploration of the interaction between cognitive flexibility and analogical reasoning as the ability to shift attention from one representational point of view to another develops quite lately (Chevalier & Blaye, 2006; Diamond, 2013). Thus, one of the goals of the present dissertation was to investigate how limitation of cognitive flexibility in early childhood affects the ability to efficiently reason by analogy. Once again, theories of analogical reasoning development do not make specific accounts of how visual strategies should be affected by the development of executive functions, and to our knowledge, no account of analogical reasoning development has taken into account the ability to flexibly shift from one representation to another when reasoning in their description of the phenomenon in children. The only models that are able to simulate representational flexibility are Copycat and Tabletop. Thus, by decreasing the temperature of the models more rapidly when simulating children than when simulating adults, these models could simulate potential lack of flexibility.

V.e. Summary of the goals

In summary, the goals of the research presented here are to study the effect of goal maintenance and goal neglect, and executive functioning in children's and adults' ability to reason by analogy. To do this we used different types of measurement: accuracy of the answer, reaction times, but also the visual behavior of our participants, which has not been studied to a large extent yet. However we believe that studying visual strategies is relevant for achieving these goals, as the precedent review of the literature on eye movements and their relation to cognitive and executive processes shows.

Visual strategies in scene-oriented analogical problems

Chapter II: Visual strategies in scene-oriented analogical problems

I. Background

In the present chapter, we wanted to study adults' and children's visual strategies in a task commonly used to assess children's analogical reasoning (i.e., the scene analogy task; Richland, Morrison, & Holyoak, 2006), and to know if the visual strategies of Thibaut, French, Missault, Gérard, & Glady (2011) generalized to this task. In the Scene Analogy task, participants have to find what plays the same role in the target scene (e.g. the boy who is chasing a girl, see Figure 3) as the element that is pointed to in the source scene (e.g., a cat chasing a mouse). One of the specificities of this task is to use scenes rather than separated pictures as the basis of the analogical comparison and reasoning. Recent evidence suggests that grouping objects in meaningful scenes might positively affect attention toward these objects and their relations (see Humphreys et al., 2010 for a review). Another specificity is its focus in terms of goals on the mapping of one domain on the other. Both these aspects differ from the A:B::C:? task. Indeed, the goal of the A:B::C:? task (see Figure 3), given by the instructions, is to find a solution related to C as B is related to A, which put a high focus on C and what is related to it, especially for children (Thibaut, French, Missault, et al., 2011).

The scene analogy task has been used by Richland et al. (2006) to show that younger children were subject to more relational errors (i.e., choosing an object involved in the correct relation but having the wrong role: the girl in Figure 3) and distractor errors (i.e. choosing objects which look like the one pointed in the source picture but which do not have the same role: the cat in the bottom picture in Figure 3) than older children and adolescents. This was interpreted in terms of inhibition capacities in analogical reasoning which develop gradually through childhood and adolescence. However, relational errors could be linked to goal neglect as one of the goals of the task is to align the roles of two objects involved in a similar relation. Another finding of this study is the increased difficulty for children to find the correct answer when the relational complexity is increased (i.e., when the number of relations which have to be taken into account at the same time increases). For example, children had more difficulties to find the correct answer when presented with a dog chasing a cat which was also chasing a mouse, and a mother chasing a boy who was chasing a girl, than in the previous example with simply a dog chasing a cat, and a boy chasing a girl. This result was linked to Halford's Relational Complexity theory (Halford et al., 1998; Halford, 1993) which states that the development of the ability to handle more and more relationally complex materials in working memory is a major factor in children's cognitive development. However, once again it can be interpreted in terms of goal neglect by children, as ternary relations are supposed to be available to 5-year-old children in Halford's theory.

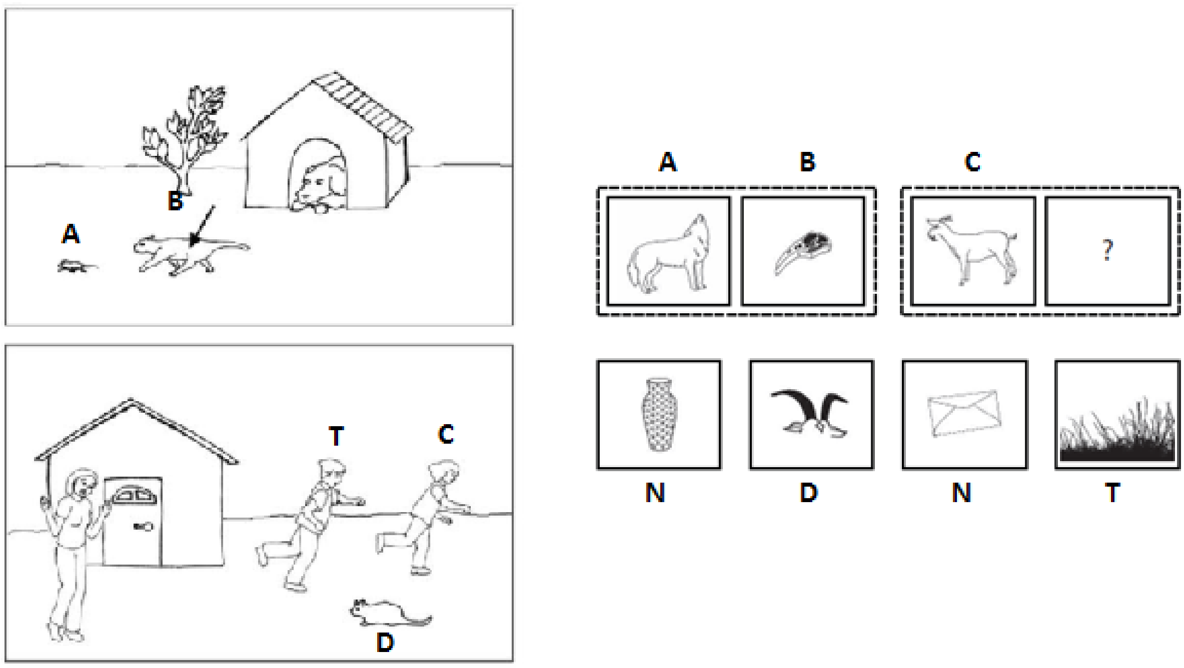


Figure 3: Sample materials for the Scene Analogy task (left panel, Richland et al., 2006) and the A:B::C:? task (right panel, Thibaut et al. 2010b). Corresponding letters in the two tasks show corresponding roles in the structure of the task. For instance, T elements in both tasks are the solutions, B elements are the elements which play the same role as T in both tasks, A elements are the element involved in a relation with B, D to Distractors and so on.

Richland et al.'s (2006) study was followed by an eye-tracking experiment with the same task by Gordon & Moser (2007). They showed that there were longer fixations on the stimuli with an arrow pointing to it in the source scene and its match in the target scene, that the frequencies of saccades between the extra objects (the dog and the mother, in our previous example, which were present in both low and high relational complexity conditions) and other objects within the scene were higher when the extra objects were involved in a relation with the other objects than when they were not, even though it was not paralleled by higher fixation durations on these extra objects. Other frequent saccades were between the two related objects that constituted the heart of the analogical problems within the source and target domains (e.g., the cat and the mouse on one hand, and the boy and the girl on the other). These results might be the mark of a task-related bias toward specific information in the material (i.e., objects that are involved in relations).

Another previous study on visual strategies in analogical reasoning is Thibaut, French, Missault, et al.'s (2011) study on children's and adults' eye movements during the solution of A:B::C:? problems. They found that participants focused mainly on C and the solution when looking at overall fixation times. The saccades which were the most frequent were the saccades between A and B, and between C and the solution. These saccades between elements either in the source or in the target domain can be linked to the encoding of the relations in each domain compared in the analogical problem. Another saccade which was frequent was the saccade between the solution and the related-to-C distractor, which might be related to the comparison of the different elements that are related to C to find the one which has a relation to C similar to the one B has to A. Differences between adults and children were found in their fixation times on the related-to-C distractor. Children looked longer to these distractors than adults, suggesting difficulty for them to inhibit the information coming from these stimuli. Another important finding was that children were attracted by the target domain (i.e., C and the solution set) already in the first third of the trials, whereas adults spent the first third of trials mainly on A and B, looking at C and the target domain only after. This can be explained by children's difficulty to maintain the goals of the task. Thus, they might be unable to maintain the goal of similarity between the relations of the two domains compared.

This focus on relations within domains found in both the A:B::C:? and the Scene Analogy task, as suggested by the preponderance of saccades between the elements of the same domain, is not predicted by the first theories of analogical reasoning (i.e., the Structure Mapping Theory and the Multiconstraint Theory). On the contrary, these theories would predict a larger focus on the correspondences between the domains, observable by between domains saccades (i.e., A to C and B to T saccades) than what was found in the preceding studies. The LISA model and the Path-Mapping Theory would predict a focus on the within-domain relations rather than on the between domain correspondences. However, when LISA would only predict that relations related to the goals of the subject would be visually explored to a larger extent than those who are not related to the goals of the subject and would achieve a complete mapping of the two domains but no difference between the task in terms of patterns of eye movements, the Path-Mapping Theory makes the prediction that only correspondences between the domains which are relevant to the goals of the task will be considered. Hence, the latter would predict differences in the eye movements of participants in the A:B::C:? and the Scene Analogy task. As the goal of the first task is simply to find a relation that is similar, it would not predict an alignment between the two domain but simply the encoding of the two domains relations, and the comparisons of elements that are related to C in terms of the relations they have with C. In the second task, the Path-Mapping Theory would predict a specific alignment between the goal elements in the source and the target domains (e.g., the cat and the boy). As children are less able to maintain goals than adults, it would also be predictable that children would make less eye movement patterns related to the goal of the task, i.e., saccades between the two goal objects.

To test these hypotheses, we designed three experiments. In the first experiment of this chapter, we studied the visual strategies of adults and children in the Scene Analogy task, in order to reproduce and extend previous results from Gordon and Moser (2007) to children, and find if children's relational errors could be due to goal neglect. Then, in the second experiment, we compared these results with an A:B::C:? task, with AB on one hand and C and the solution set on the other, put within meaningful scenes to specifically test if the different goals of these tasks affected differently visual strategies in adults and children. Indeed, the Path-Mapping Theory would make different predictions about the visual strategies used in these two tasks, as explained above. The Scene Analogy task should rely more on an explicit mapping between the two domains' goal elements, when the A:B::C:? task should not, because enough information to solve the main goal of the task is gathered when the source and the different relation in the target domain are encoded and found similar. These two tasks were finally compared with a standard presentation of the A:B::C:? task in the third experiment. In fact, differences have been shown in participants' attention toward objects and relations when the materials are presented in meaningful scenes or as separated objects (Humphreys et al., 2010). Indeed, attention toward relations seems to be greater in the first case. Thus, we expected that children would benefit from scene presentations, and that it would be visible in their visual strategies.

II. Experiment 1: Visual strategy of children and adults in a Scene Analogy Task.

II. a. Objectives and Hypotheses

The objective of this experiment was to observe the visual strategies of children and adults in a task commonly used to assess children's analogical reasoning: the Scene Analogy task. This task's goals are centered on the mapping of the source domain on the target domain to find the solution, focusing especially on a "what is like the item pointed to" goal which prompts participants to compare the item with an arrow in the source with items in the target. We expected visual strategies in children and adults to be coherent with the Path-Mapping Theory predictions exposed above, i.e., that participants would focus on within-domain relations, and also on the correspondence with the objects specifically linked to the goal of the task. We thus hypothesized that this task would elicit a great focus on the item with an arrow and the solution, and the comparison between their roles. In addition to this, as children are less able to maintain goals and to keep irrelevant information than adults, we also expected children to make a lower number of saccades between the two goal objects (the item pointed to with an arrow and its correspondent in the target domain, e.g., the cat and the boy of our example above) and to show more interest in the distractor looking like the item with an arrow, because of lower inhibition abilities.

Our first hypothesis was a general age effect on behavioral data, with adults finding more correct answers than children, and children making more relational errors (i.e. choosing the element that is related to the solution) and distractor errors (i.e. choosing the element perceptually similar to the item with an arrow) than adults, as Richland et al. (2006) found.

As the Path-Mapping Theory would predict encoding of an extensive encoding of the relational structure between the elements in each domain, we expected a high level of saccades between the pointed item (called later B because it is the element playing the same role as the target T of the problem in the target domain, as B elements in A:B::C:? problems) and the element involved in a relation with it (called A because of this relation to B, as A elements in A:B::C:? problems), and of saccades between the solution and the item it interacts with (called C because it is involved in a relation with T, as C elements in A:B::C:? problems) which are crucial for determining the roles of the item pointed to and the solution.

As the task is essentially centered on the mapping of the item with an arrow on something in the target domain on the basis of its role, we expected that the item pointed to and the solution would be of particular interest for participants (i.e., would be fixated longer than other stimuli). We also expected that the saccade between the item with an arrow and the solution (BT saccade) would be a strong component of participants' visual strategies because it might be implied in the comparison of the roles of the two stimuli. These patterns are also predicted by the Path-Mapping Theory (see section III.b. of chapter I for the details of this theory). From a developmental point of view, a possible hypothesis would be that children's difficulty to maintain the goals of the task might make them less attentive to this information, thus making less BT saccade.

If the distractors play their role, it should also elicit long fixation times and a great number of saccades implying it, especially saccades between the item pointed to and its perceptually similar item (BDis saccades) which might be implied in the alignment of these elements, and saccades between the solution and the distractor (TDis saccades) which might be involved in the comparison of the possible answers. From a developmental point of view, as children have lower inhibition ability than adults, we expected that these markers of the distractors effect would be found at a higher degree in children than in adults.

II. b. Methods

Participants

Participants were 25 6-to-7-year-olds (10 females, 15 males; M=77.5 months; SD=4.6; from 72 to 92 months) and 29 adults (25 females, 4 males; M=21 years; SD=4.4; from 17 to 40), who were students of the University of Burgundy. Participants were naïve to this task, they participated voluntarily, and we required parent's informed consent for children to participate to the experiment.

Materials

The tasks consisted in 14 trials (3 training and 11 test trials) presented in a random order. Each problem was composed of 7 black and white line drawings displayed in two scenes (501x376 pixels) displayed one on the top of the other and both framed in a black rectangle (Figure 4). We named these seven pictures after the nomenclature used in the previous tasks, based on their relation to the target item and to their roles in the problem matching to those in the A:B::C:? task. Thus, in the top scene (i.e., the source scene), there was two items (A and B, B playing a role equivalent to the Target's role in the Target scene). The remaining 5 pictures (i.e., C which was in a relation to the Target similar to the one between A and B, T which was the correct answer, a distractor Dis; and 2 Unrelated objects U which were not related to the problem) were presented in the bottom scene (i.e., the Target scene). Each scene was presented with a minimal context (i.e. horizon line, floor and walls joins).

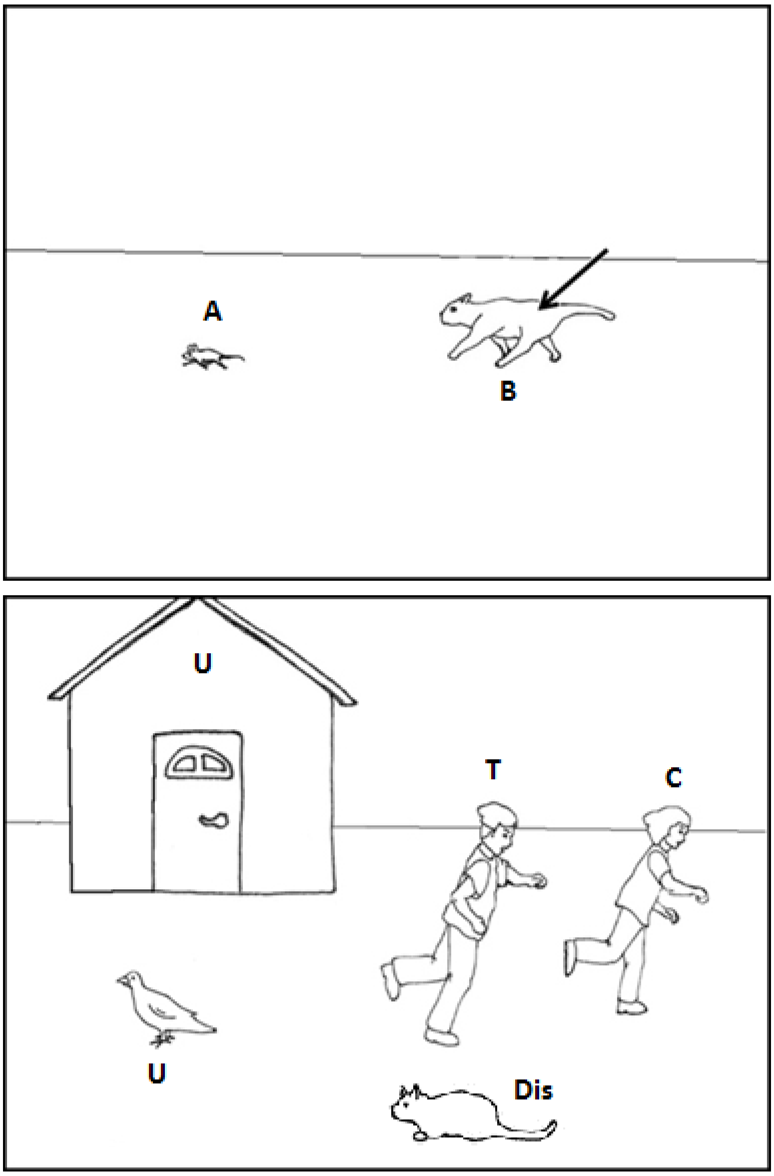


Figure 4: Sample materials from Experiment 1

These pictures were previously used by Richland, Morrison, & Holyoak (2006). They chose the distractors to be perceptually related to the B stimulus which was the center of the task's instructions as the main goal is to find something that plays the same role in the target scene as the B stimulus plays in the source scene. An arrow pointed to B to indicate to participants which stimulus in the source scene had to be matched in to a stimulus in the target scene. The U stimuli were parts of the scene's context (i.e., houses, trees, etc.) thus providing "ecological" validity to these stimuli. The scenes were slightly modified from the original ones to match the number of distractors and to provide suitable analysis of participants' scanpaths (i.e., we spaced each stimulus to provide distinct areas of interest).

We presented these problems on a Tobii T120 eye-tracker (resolution: 1024x768). E-prime software (version 2.8.0.22) was used to construct the experiment, itself embedded in a Tobii Studio (version 2.1.12) eye movement recording procedure. Data were analyzed using Statistica 8 software.

Procedure

The experiment took place in a quiet room in children's schools or in an experimental box at the University of Burgundy for adult participants. Participants were tested individually. In order to avoid any difficulty due to a poor recognition or a lack of knowledge of the stimuli, we presented each picture individually and asked participants to name the objects which were represented. When they were unable to name one stimulus, they were asked if they knew how it was used or where it could be found. After this first phase, the eye-tracker was calibrated using a Tobii Studio built-in calibration procedure.

After this calibration procedure, the analogical reasoning task took place. During the first training trial, participants were instructed as follows: "In each problem, there are two scenes in which the same thing happens. Can you see why the same thing happens?" In case of error (i.e., answer not based on the similarity between the actions performed in each scene, for instance, the distractor error), the experimenter gave the correct answer. After this, the experimenter continued: "Can you see the arrow pointing at this thing [B]? This means you have to find in the bottom picture [pointing at it] which thing plays the same role as this one [B] in the top picture." The experimenter explained what role meant as "doing the same thing” or “being in the same position”. Participants were asked to justify their answer, basing their justification on the role played by the B and T pictures. When it was correct, the experimenter gave a positive feedback. Otherwise, he gave the correct answer and justification based on the roles of B and T, and explained the task again. Feedbacks were given in all training trials as explained above. Instructions and feedback were not prvided in the test phase of the experiment.

The third phase of the experiment was a second control task. Participants had to give the relation holding between all the A:B pairs, and all the CT pairs used in the experiment, one by one. This was done to remove from the analyses all the trials that were failed because of an absence of knowledge/recognition of the relation composing the problems from analyses.

II. c. Results

Overall, less than 1% of the stimuli were not recognized. One trial was excluded for the analyses because the relation used to compose the analogy was not known by 20% of participants. Apart from this particular trial, only one trial in one participant's data was removed from subsequent analysis because of an absence of knowledge of at least one relation composing the problem. Ten trials were also removed from analyses because reaction times were not recorded due to an absence of mouse click of the experimenter. These trials were included in the score analysis but not in the reaction time and eye movement analyses. In addition, 15% of the trials were removed because more than 50% of the eye-tracking data were missing. These trials were included in the score and reaction time analyses but not in the eye movement analysis. This resulted in two 6-to-7-year-olds not having data and thus excluded from this analysis.

Behavioral data

We first compared the two age groups performance in the analogy task using a two-tailed independent t-test (see Figure 5, top left panel), testing our hypothesis that children would have lower response accuracy than adults. It indeed revealed a significant difference in scores ($t(52)=4.4$; $p<.001$; $\eta^2_p=.270$) with better performance by adults than children.

We also analyzed patterns of errors (Figure 5, top right and bottom left panels), and especially relational and distractor errors, predicting higher rates of these errors in children than in adults. We ran a two-tailed independent t-test to compare the number of relational errors (i.e., choosing the other element involved in the relation of the target picture instead of the correct one) in the two groups. It revealed a significantly larger number of these errors in children than in adults ($t(52)=3.1$; $p=.003$; $\eta^2_p=.156$). The same analysis was run on the distractor errors. It revealed the same pattern of results ($t(52)=2.7$; $p=.008$; $\eta^2_p=.126$), thus confirming both our hypotheses about number of errors, suggesting children had difficulty to inhibit the information coming from the distractor, and to maintain the goal of role comparison in the relations.

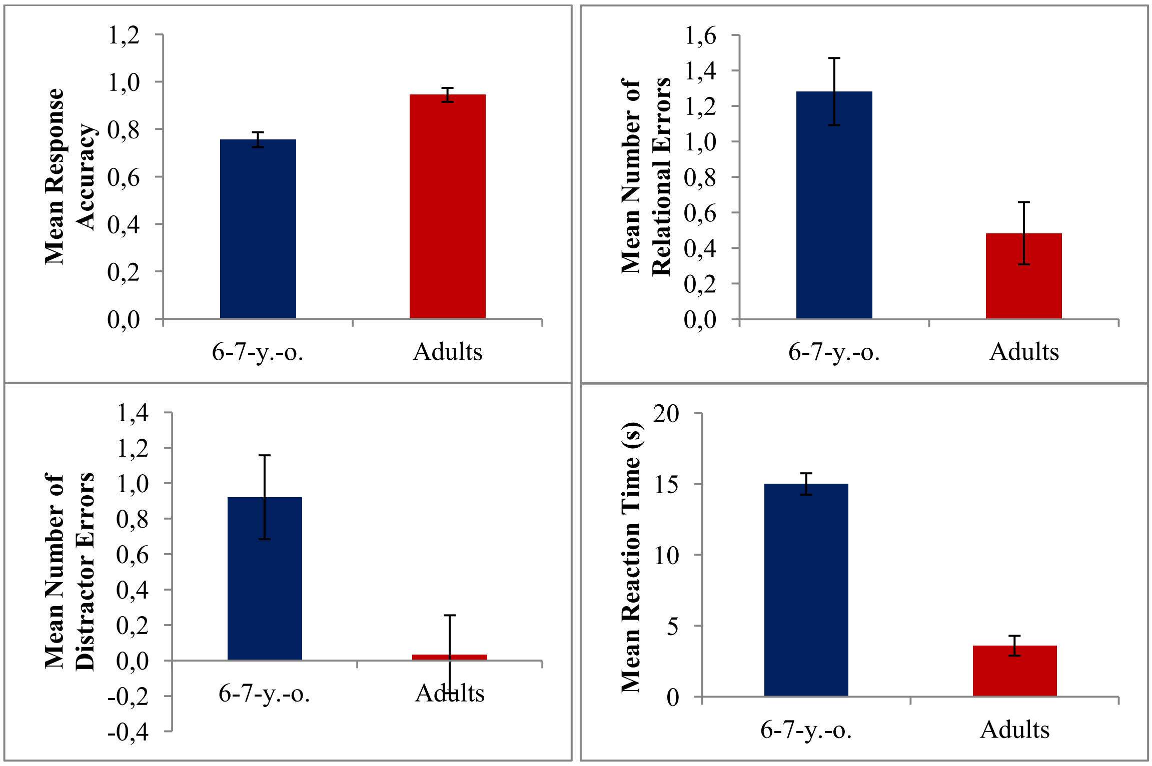


Figure 5: Mean response accuracy (upper left panel, maximum = 1), number of Relational (upper right panel) and Distractor (lower left panel) errors, and reaction times (lower right panel) by participant in 6-to-7-year-olds and adults in the Scene Analogy task (error bars represent SEM).

Finally, to determine which type of data we should use for eye movement analyses (i.e., absolute values or percentage), we analyzed reaction times in the two groups (Figure 5, bottom right panel). A two-tailed independent t-test revealed a significant difference between the two groups ($t(52)=11.1$; $p<.001$; $\eta^2_p=.703$) with longer reaction times for children than for adults. We thus used percentage of total fixation time and of total number of saccades in the eye movement analyses.

Visual strategies in the Scene Analogy task

Because of longer reaction times in children than in adults, we scaled eye-movement data to make them comparable between age groups by using percentage of total fixation and percentage of total number of saccades as dependent variables instead of absolute times of fixation and number of saccades.

First, we analyzed the percentages of fixation of each stimulus in the two age groups, running a two-way mixed ANOVA with Age (6-to-7-year-olds, adults) as a between-subject factor and Type of Stimulus (A, B, C, T(arget), Dis(tractor, perceptual), U(nrelated distractors)) as a within-subject factor (see Figure 6), expecting longer fixations on B and T due to the goal of the task, and longer fixation percentage on Dis in children than in adults. It revealed a significant main effect of Type of Stimulus ($F(5,250)=324.9; p<.001; \eta^2_p=.867$) and a significant interaction between Type of Stimulus and Age ($F(5,250)=26.1$; $p<.001$; $\eta^2_p=.343$).

Planned comparisons confirmed that mean rates of fixation of B and T were higher than mean rates of other stimuli (respectively: $F(1,50)=203.9$; $p<.001$; $\eta^2_p=.803$; $F(1,50)=337.7$; $p<.001$; $\eta^2_p=.871$). This confirmed our hypothesis that the focus of attention of this task would be the goal objects (i.e., the object with an arrows pointing to it and the one having the same role in the target domain). Overall, Dis was not looked at a high rate. Its mean fixation rate was significantly lower than the mean rate of fixation of other stimuli (planned comparison: $F(1,50)=490.9$; $p<.001$; $\eta^2_p=.908$). The distractor thus did not seem to play its role of distractor, i.e. it did not catch participants' attention. The planned comparison between adults' and children's fixation of Dis was significant ($F(1,50)=13.9$; $p<.001$; $\eta^2_p=.218$), confirming our hypothesis about longer fixation of Dis in children than in adults.

We were also interested in the rates of saccades, especially the rates of inter-domain mapping of corresponding elements (AC and BT saccades), the first predicted not to be frequent, when the second would be more frequent because of its link to the goals. We also wanted to compare intra-domain saccades (i.e., AB and CT saccades) with other types of saccades, and predicted a higher rate of them than other types of saccades. BDis saccades were also of interest as they might be related to children's inability to inhibit the irrelevant information from the distractor, and thus predictive of distractor errors, more numerous in this age group. We thus analyzed participants' percentage of saccades between pairs of stimuli (Figure 7) with a two-way mixed-ANOVA design with Transition (AB, AC, AT, ADis, AU, BC, BT, BDis, BU, CT, CDis, CU, TDis, TU, DisU) as a within-subject factor and Age (6-to-7-year-olds, adults) as a between-subject factor. We found a significant main effect of Transition ($F(14,700)=144.3$; $p<.001$; $\eta^2_p=.743$) and a significant interaction between Age and Transition ($F(14, 700)=13.6$; $p<.001$; $\eta^2_p=.214$).

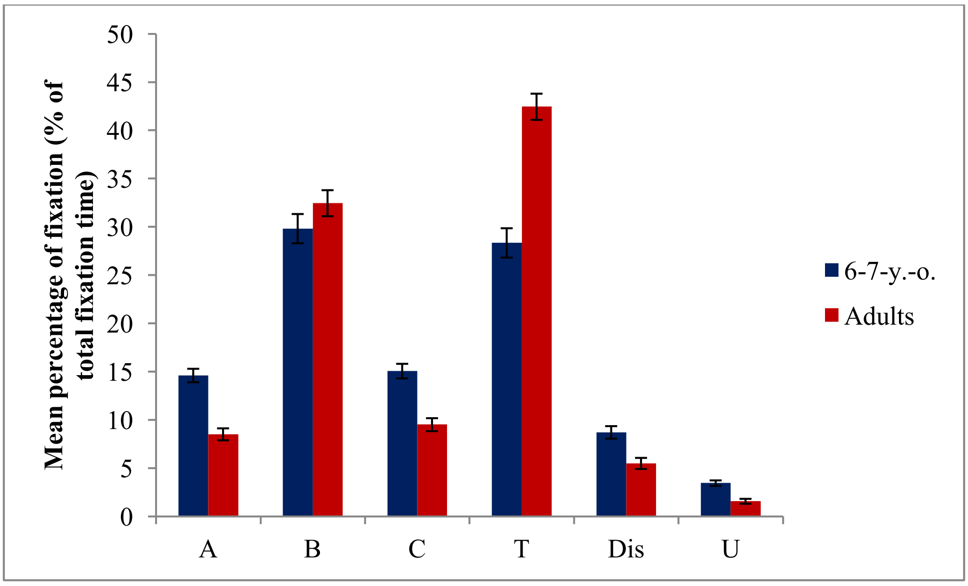


Figure 6: Mean Percentage of fixation of each stimulus in 6-to-7-year-olds and adults (error bars represent SEM).

Planned comparisons confirmed that mean percentage of AB, BT, and CT saccades were higher than mean percentage of other saccades (respectively: $F(1,50)=240.7$; $p<.001$; $\eta^2_p=.828$; $F(1,50)=57.1$; $p<.001$; $\eta^2_p=.533$; $F(1,50)=239.9$; $p<.001$; $\eta^2_p=.828$) suggesting that these saccades were important in participants' strategies. AC saccades were not frequent: their frequency was lower than the mean frequency of other saccades ($F(1,50)=213.1$; $p<.001$; $\eta^2_p=.810$). These results, taken together, confirm the prediction of the Path-Mapping Theory. However, the BT saccade rate was significantly lower in children than in adults ($F(1,50)=43.5$; $p<.001$; $\eta^2_p=.465$), confirming that children made less saccades related to the main goal of the task. Overall, there were less BDis saccades than other saccades ($F(1,50)=57.1$; $p<.001$; $\eta^2_p=.533$). This is coherent with the low fixation of Dis found in the previous analysis on percentages of fixation and further suggests that the distractor did not catch participants' attention. The rates of BDis saccades did not differ between adults and children ($F(1,50)=2.5$; $p=.123$; $\eta^2_p=.048$), which is not coherent with the difference expected.

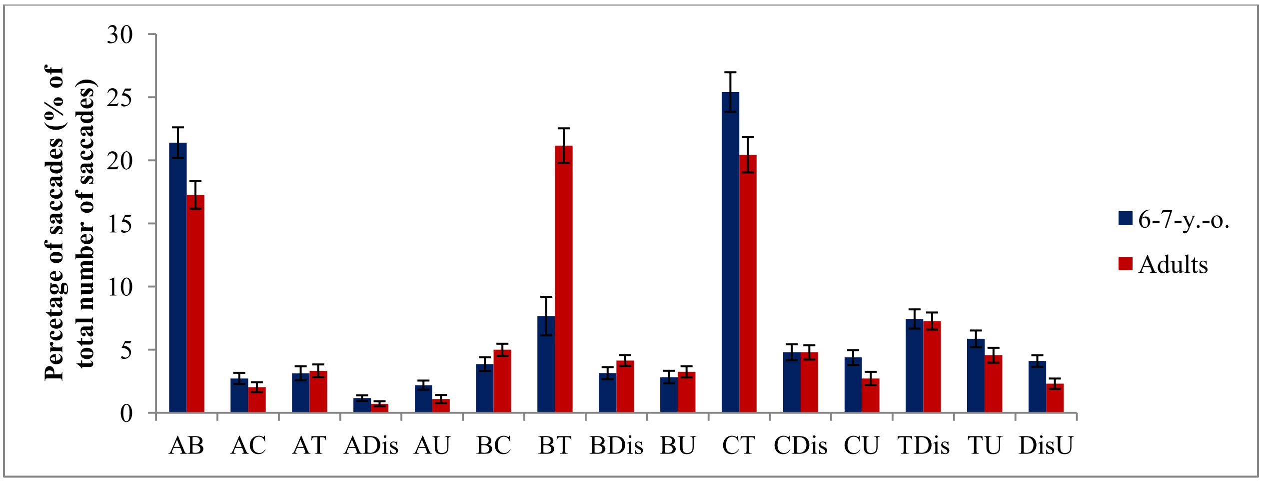


Figure 7: Mean Percentage of each type of saccade in 6-to-7-year-olds and adults while solving Scene Analogy problems (Error bars represent SEM).

II. d. Discussion

The Path-Mapping Theory makes predictions about the eye movement patterns in the Scene Analogy task. It predicts that participants would focus more on the goal objects of the task (i.e., B and T), would make within domains saccades to encode the relations relative to each domain compared, and between the two objects corresponding in terms of roles which are at the center of the main goal of the task. As children experience difficulty maintaining goals over time (Marcovitch et al., 2010), we expected that these types of comparison would be less present in them than in adults, and as they make more distractor errors (Richland et al., 2006), we predicted more fixations on the perceptually-related-to-B distractor as well as more saccades involving B and this distractor in children than in adults, suggesting a lower ability to inhibit irrelevant information when solving an analogical reasoning task.

The present results bear out the prediction made by the Path-Mapping Theory about visual strategies in the Scene Analogy task. Participants focused on the stimuli that were relevant to the specific goals of the task (i.e., B and T), and made more saccades between these two elements and those linked to them by a relation in the source and the target pictures (i.e., AB, and CT saccades). These intra-domain saccades might be related to participants trying to find the roles of the different stimuli taking part in the relation represented in the scenes. These roles might be kept active in working memory, and actively compared and aligned by the participants by making BT saccades. The other fixation times and number of saccades were comparatively low, meaning they were not particularly informative to participants while solving the problems (Deubel & Schneider, 1996; He & Kowler, 1992). Note that the Path-Mapping Theory is the only theory predicting a mixed pattern of rates of saccades in this task (i.e., high rates of within-domain saccades to encode the relations, and high rates of between-domain saccades linked to the goal of the task). Other theories would predict either more within-domain or more between-domain saccades.

Even though our analysis differed from those used by Gordon & Moser (2007), we also found a great amount of fixation on goal objects (i.e., B and T) and the elements which were related to them (i.e., A and C), and a high rate of saccades between these objects. However, due to differences in the analyses used, we cannot compare their results about the saccades between the object with an arrow in the source and the corresponding item (in terms of role) in the target with our data. It is possible that these authors overlooked the importance of this type of saccade, as they mainly focused on intra-domain saccades and did not report the values of BT saccades. These authors also reported greater fixation density on distractor object than on a control object perceptually dissimilar to B, which suggests that even adults paid attention to these distractors. Even if they did not compare it directly to the fixation times of objects implicated in the relation, the fixation time of the distractor is close to the one observed in objects involved in relations with goal objects. This was not found in our results, which can be explained by the shift of instructions ("what play the same role as the object pointed at?"), theirs ("what is like the object pointed at?") being ambiguous about the type of similarity which had to be considered (perceptual or role similarity).

There were two types of errors in this task — namely, relational and perceptual distractor errors. Children made both at a higher rate than adults. These results concur with previous results obtained by Richland et al. (2006), although our children's response accuracy in this study were 10% higher than in theirs. The higher rates of errors in children than in adults were observed along with longer looking times on perceptually-similar-to-B distractors, and lower rate of BT saccade. Thus, children's relational errors might result from the low number of saccades between B and T, because this saccade might be involved, as explained above, in the alignment of the two elements based on their roles, and in the comparison of these roles. This might also be crucial for evaluating the accuracy of the answer chosen before giving it. Therefore, children seem to overlook the comparison and judgment of role similarity of their answer with the role of the stimulus pointed to in the source scene. This might have led them to give answers only on the basis of the relation inferred through CT saccades but not on the basis of the roles of the actors taking part in this relation, leading to relational errors. These results can be explained in the framework of goal maintenance. Children, experiencing difficulty to maintain the goal of the task might forget to make the comparisons that are relevant to this goal, i.e., comparisons between B and T.

Children also made more distractor errors than adults. This effect of distractors on the performance of children was accompanied by longer looks at distractors. Nevertheless, other saccades involving the distractor were not more frequent than in adults. However, although children spent more time looking at the distractor than adults, this stimulus was looked at to a low extent when compared to other stimuli. This can be related to the fact that 65% of the distracting errors were made by only 3 children. Hence, it is possible that these 3 children did not understand the task. Most children did not focus on perceptually-similar-to-B distractors. The fact that these distractors did not capture children's attention can explain why our young participants performed better than Richland et al.'s (2006) participants of the same age. This increased response accuracy might be due to our change of instructions which rendered the task clearer and thus excluded the perceptual distractor as a potential answer. Indeed, we asked participants to find the thing which "played the same role as the one with an arrow pointing at it", when Richland et al. asked "who is like the stimulus with an arrow". The term "like" is ambiguous regarding the type of comparison which is expected (i.e., perceptual or role-based), and, consequently, could lead to a greater number of similar-to-B distractor errors.

The present results indeed suggest that participants have a specific visual strategy in the Scene Analogy task which might be due to specific goals of this task, and that children's relational errors might be due to a neglect of the main goal, i.e., comparing the picture pointed to with the solution they want to give in terms of roles. It might be that a difference exist between visual strategies in this task and in the A:B::C:? task (Thibaut, French, Missault, et al., 2011). Experiment 2 of this chapter is dedicated to the direct comparison of these two tasks.

III. Experiment 2: Comparison of visual strategies in scene analogy and a scene-oriented A:B::C:? tasks

III.a. Objectives and Hypotheses

Differences in visual strategies between the A:B::C:? tasks (Thibaut, French, Missault, et al., 2011) and the Scene Analogy task (Experiment 1, this chapter) could not be directly tested with the previous setting. In the present experiment, the objective was to reproduce results from Thibaut et al. (2011), and to compare the Scene Analogy task and the A:B::C:? task directly. We expected that the focus of tasks in terms of goals might elicit different visual strategies and processes to solve them, with the Scene Analogy task having more mapping requirements, especially between the two goal objects, when the A:B::C:? task should elicit exclusively relation encoding and comparison within domains.

The Path-Mapping Theory seems to best explain results from Experiment 1, and is also compatible with results obtained by Thibaut, French, Missault, et al. (2011). This model predicts that participants in both tasks would make within-domain comparisons (i.e., AB and CT saccades) to find the relations in each domain. However, it also predicts different rates of BT saccades in each task, but a low rate of AC saccades in both cases, in contrast to the Structure Mapping Theory, the Multiconstraint Theory, and LISA. The Within-Context A:B::C:? task should thus elicit less BT saccades than the Scene Analogy task, because of the latter's goals being focused on the correspondences between B and T in terms of roles, but not the former's. Another predicted difference between the two tasks is the rate of fixation of B and C. The Scene Analogy task should elicit more fixations on B than other stimuli, and the A:B::C:? task should elicit more fixations on C. Thus, participants should look longer at C in the A:B::C:? task than in the Scene Analogy task, and vice versa for B, because of the difference of focus of the goals of the task on these elements.

As a consequence of maturation of goal maintenance abilities, children should display less BT saccades than adults in the Scene Analogy task, and less AB saccades and fixations on A and B than adults in the A:B::C:? task, as previously shown (Experiment 1, Thibaut, French, Missault, et al., 2011). Indeed, children seemed to neglect the goal of similarity between the relations between A and B, and C and T in the A:B::C:? task, focusing to a large extent on the target domain (C and the solution set) in this study. Children should also display more relational errors than adults in the Scene Analogy task, this type of error being potentially due to the neglect of the alignment of B and T and the comparison between their roles.

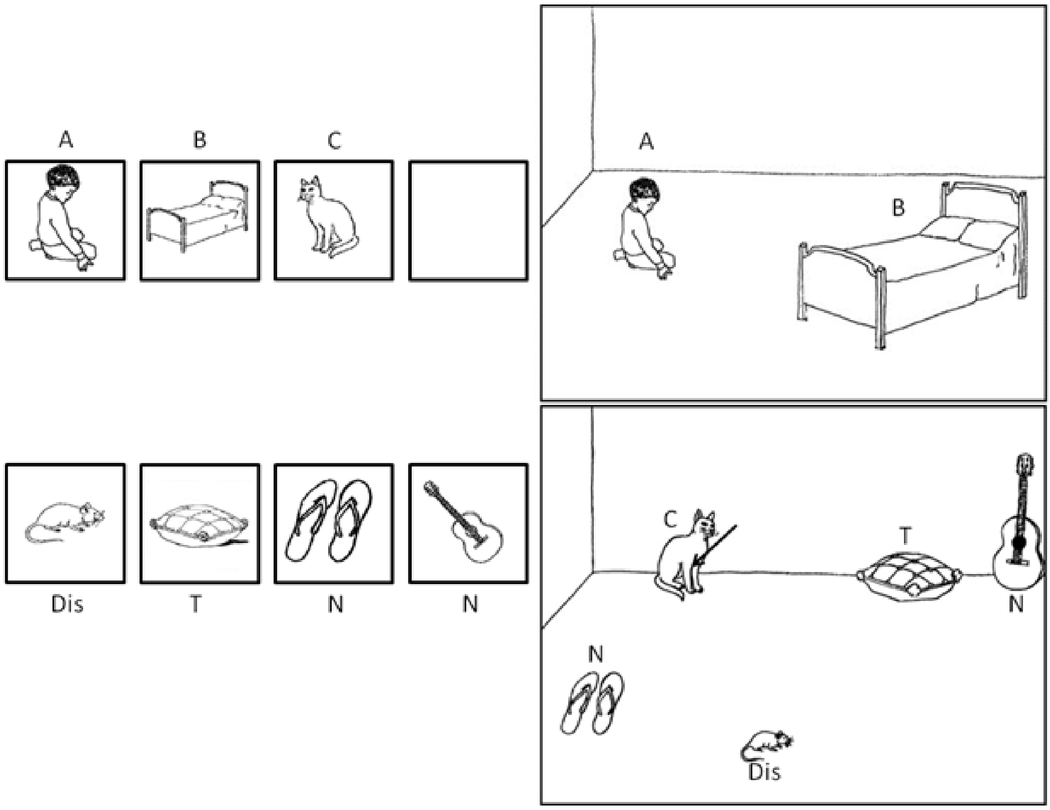


Figure 8: Example of a standard A:B::C:? problem (left panel) transformed in a Within-Context A:B::C:? trial (right panel).

As the distractor did not seem to catch attention in the Scene Analogy task, probably due to its irrelevance to the goal of the task in the Scene Analogy task, we expected a difference in the number of distractor errors between the two tasks. We also expected the percentage of fixations to the distractor in the A:B::C:? task to be greater than in the Scene Analogy task.

Regarding the development of executive function and their involvement in analogical reasoning, and especially inhibition, we expected higher rates of distractor errors and lower scores in children when compared to adults in the Within-Context A:B::C:?. These higher error rates and lower scores in children can be attributed to immature inhibition capacities. Hence, they should make greater efforts to inhibit the information coming from the distractors and eventually fail to inhibit this information. Thus, distractors should be fixated longer, and CDis saccades should be more frequent in children than in adults in the Within-Context A:B::C:? task due to the maturation of inhibition.

To test these hypotheses, we used an Age (6-to-7-year-olds, adults) x Task (Scene Analogy, Within-Context A:B::C:? task) design with Age as a between-subject factor, and Task as a within-subject factor. Thus, each participant was tested in both tasks. We recorded participants' scores, reaction times and eye movements. To minimize differences in the presentation of the two tasks, we therefore constructed a variant of the A:B::C:? task which we called the Within-Context A:B::C:? task (see Figure 8). In this task, we put A and B in one scene, and C and the solution set in another, presented in the same way as the Scene Analogy task. The Within-Context task was composed of trials from Thibaut et al. (2011), but put within a minimal scene. Thus, the instructions and what had to be done in this task were very similar to the instructions and goal of the standard A:B::C:? task except contextual cues and arrangement of stimuli. To make explicit which element was the C term, it had an arrow pointing to it. Notice that both tasks should be equally difficult because the trials we use in both tasks are equally complex (i.e., they imply one relation in each domain, and one distractor).

III.b. Methods

Participants

Twenty-five 6-to-7-year-olds (17 females, 8 males; M=75.8 months; SD = 3.5; from 69 to 82 months) and 25 adults (18 females, 7 males; M=20 years; SD=1.6; from 17 to 24 years) took part in this experiment. Adults were students at the University of Burgundy. All participants were naïve to this task and participated voluntarily. Parent's informed consent was required for children to participate to the experiment.

Materials

The task consisted in 16 trials (both 3 training and 5 test trials in the Scene Analogy and the Within-Context A:B::C:? tasks; see Figure 9) each composed of two scenes presented one above the other. The order of the two tasks was counterbalanced, and participants were assigned to one of the two possible orders randomly. Both sets of trials were constituted of two scenes (501x376 pixels each) containing 7 black and white line drawings (corresponding to A, B, C, T, Dis and 2 U, as explained above) and framed with a black rectangle. The top scene contained the A and B pictures, and the remaining ones were in the bottom scene. The only difference in the general presentation of the two tasks was that an arrow pointed to the B stimulus in the Scene Analogy task, but to the C stimulus in the Within-Context A:B::C:? task. The Scene Analogy trials were chosen among Experiment 1's trials, and those from the Within-Context A:B::C:? task were taken from Thibaut et al.'s (2011). The different pictures were put together in two scenes as explained above, and a minimal context was given (horizon lines and wall and floor joins).

These trials were presented on a Tobii T120 eye-tracker (resolution: 1024x768) by means of an E-Prime software (version 2.8.0.22) embedded in a Tobii Studio (version 2.1.12) eye-movement recording procedure. Statistical analyses were done using Statistica 8 software.

Procedure

Test sessions took place in a quiet room in children's schools or in an experimental box at the University of Burgundy for adults. Each participant was tested individually.

First participants' recognition of the different stimuli used in the trials was assessed. Each picture was presented individually and participants were asked to give its name. If they were unable to do so, they were asked say how it was used or where it could be found. If they still could not give an answer, the experimenter gave the name and a short explanation of what was the object. An eye-tracker calibration procedure followed this first phase.

Then participants were tested in the analogical reasoning task. The procedure for the Scene Analogy task was the same as the one presented in Experiment 1. In the Within-Context A:B::C:? task, participants were shown the two scenes and were given the following instructions during the first training trial: "Here are two pictures [pointing to A and B]. They go together well. Can you see why these two [A and B] go together?" Once the participant had given a relation linking A and B, the experimenter confirmed it (if it was correct) or corrected it (in case of an irrelevant relation for the solution of the problem) and continued: "OK! Do you see this one [pointing to C]? What you have to do is to find in these four pictures [pointing to the solution set] the one that goes with this one [C] in the same way as this one [B] goes with this one [A]. So, if these two [A and B] go together because [giving the relation between A and B], which one goes with this one [C] in the same way?" When participants had given an answer, the experimenter asked them to justify their answer and gave a feedback. In case of an error and/or justification, the trial was explained in terms of the relations linking A and B on one side, and C and T on the other. Instructions were repeated (with feedback) during the second training trial if the first trial was failed. Instruction and feedback were not given during test trials. Eye-tracking data was recorded when the presentation of the problem started and stopped when an answer was given.

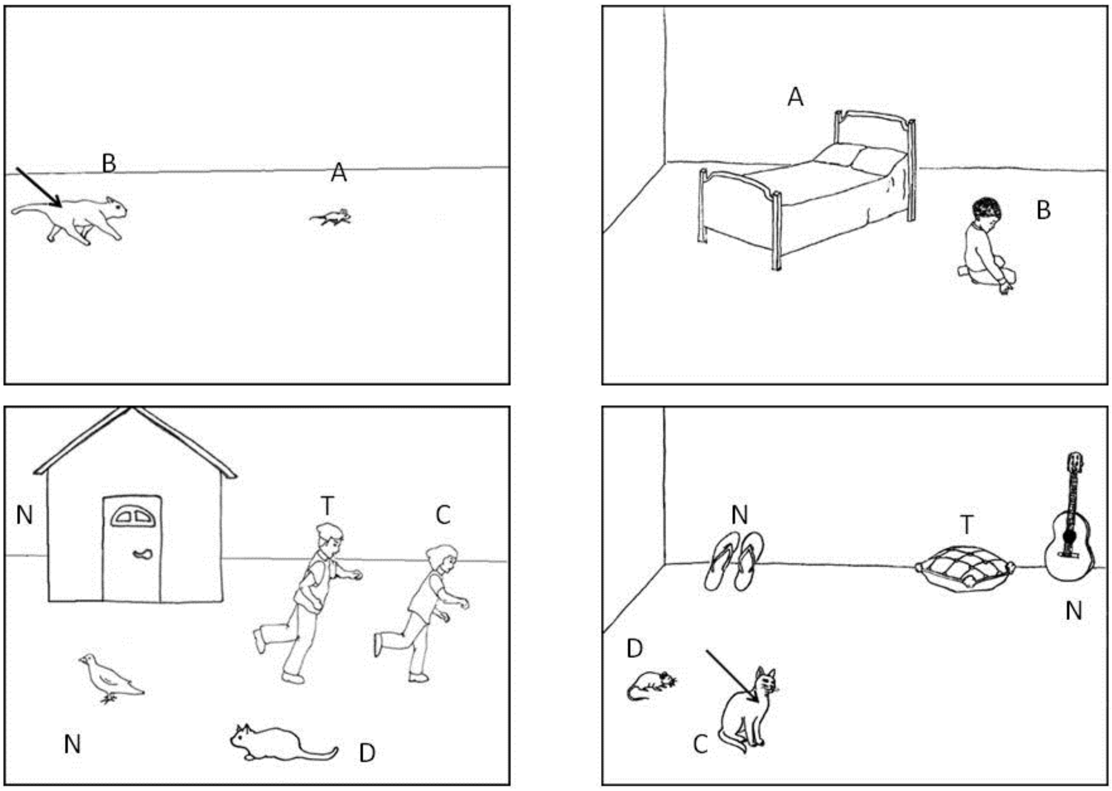


Figure 9: Sample material from the Scene Analogy task (left panel) and the Within-Context A:B::C:? task (right panel). Letters are included to specify roles of the elements, but were not presented to participants.

A third phase aimed at assessing participants' knowledge of the relation used to construct the analogical problems. To do that, we presented each AB and CT pair individually and asked participants to give the relation linking the two pictures.

III.c. Results

Overall, less than 1% of the stimuli were not recognized by participants. One of the five test trials in the Scene Analogy Task was not recognized by 20% of the participants, therefore we removed it from further analysis. Otherwise, 4 trials were removed in individuals' data due to an absence of knowledge of the relations composing them. Nine trials were removed from Reaction time and eye-tracking analyses due to an absence of recording of participants' reaction times, due to the fact that the experimenter did not press the mouse button at the end of the trial. Seven percent of the trials were removed from the eye-movement analysis because of more than 50% of missing data. This resulted in one adult not having data.

Behavioral data

To test one prediction of the executive function maturation view about the development of analogical reasoning, we analyzed response accuracies using a two-way mixed ANOVA with Age (6-to-7-year-olds, adults) as a between-subject factor and Task (Within-Context A:B::C:?, Scene Analogy) as a within-subject factor (see Figure 10). It revealed a significant main effect of Age ($F(1,48)=25.3$: $p<.001$; $\eta^2_p=.345$) with adults' response accuracy higher than children's. The effect of Task and the interaction between the two factors were not significant. This confirms partly our hypothesis about the maturation of inhibition being involved in the development of analogical reasoning, as this predicts lower scores in children than in adults.

To test this hypothesis further, we then compared children's and adults' mean number of distractor errors using the same ANOVA design (Figure 11). It revealed significant main effects of Age ($F(1,48)=13.9$; $p<.001$; $\eta^2_p=.225$) and of Task ($F(1,48)=11.9$; $p=.001$; $\eta^2_p=.198$). However the interaction between Age and Task was not significant. Thus, children made more distractor errors than adults, and more distractor errors were made in the Within-Context A:B::C:? task than in the Scene Analogy task. This suggests that inhibiting the distractor information is harder for children than in adults, and that distractors in the A:B::C:? task caught more attention than in the Scene Analogy task respectively.

In relation to the development of goal maintenance, we compared the number of relational errors (i.e., choosing the element involved in the relation of the target domain but playing the wrong role in this relation; Figure 11) in children and adults, this type of error being specific to the Scene Analogy task, using a two-sample independent t-test. Children made significantly more relational errors than adults ($t(48)=3.5$; $p=.001$; $\eta^2_p=.201$), which suggests that children had greater difficulty maintaining the main goal of the Scene analogy task, resulting in more alignment errors.

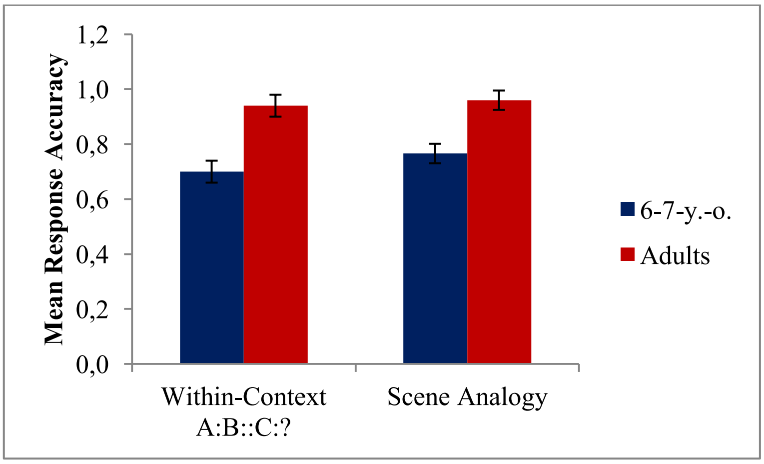


Figure 10: Mean Response Accuracy of children and adults in the Within-Context A:B::C:? and Scene Analogy tasks (Error bars represent SEM).

Finally, we analyzed children's and adults' reaction times with the same ANOVA design as presented above (Figure 12). There was a significant main effect of Age ($F(1,48)=141.5$; $p<.001$; $\eta^2_p=.747$), but neither the effect of Task, nor the interaction between Age and Task were significant. This confirmed that children had longer reaction times when compared to adults', and thus that percentage of fixation and saccades were more recommended than absolute values for eye movement analyses.

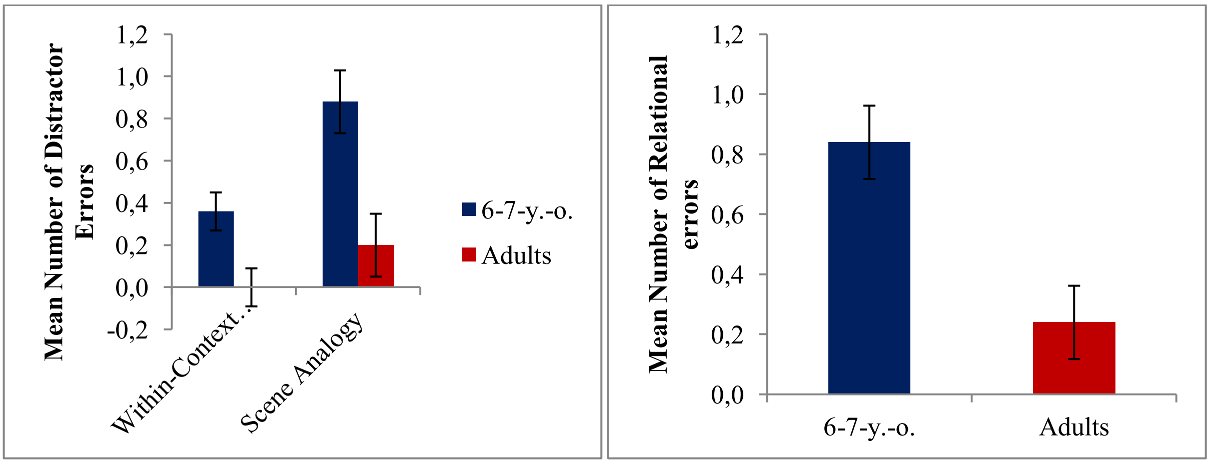


Figure 11: Mean numbers of distractor errors made by children and adults in each task (left panel) and of relational errors in the Scene Analogy task (right panel; error bars represent SEM).

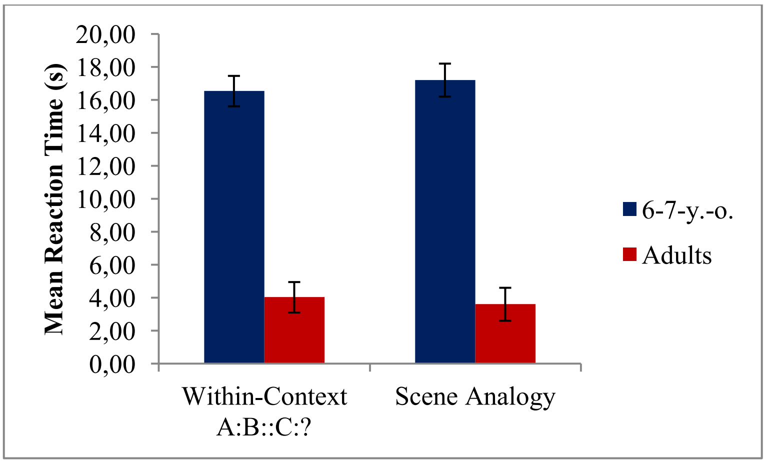


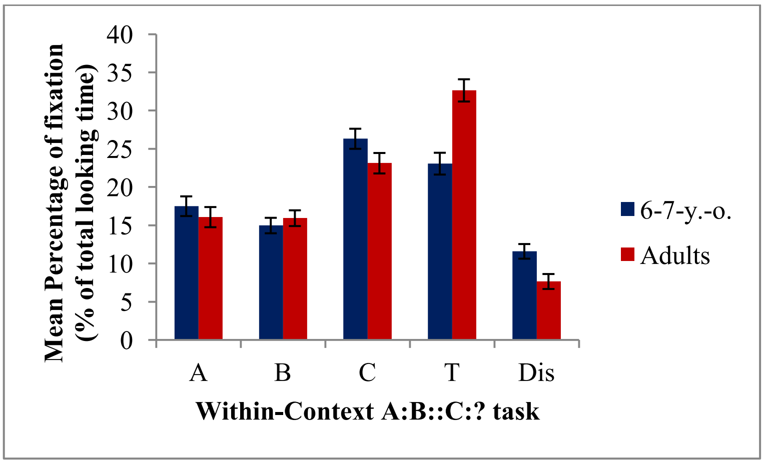
Figure 12: Mean reaction time for children and adults in the two tasks (error bars represent SEM).

Visual strategies

To test our predictions about the goals of the task affecting fixations of B, C and Dis, as well as inhibition development affecting distractor fixation and goal maintenance development affecting fixations on A and B, we analyzed patterns of fixation in the Within-Context A:B::C:? and the Scene Analogy tasks using a three-way mixed ANOVA with Age (6-to-7-year-olds, adults) as a between-subject factor, and with Type of Stimulus (A, B, C, T, Dis) and Task (Within-Context A:B::C:?, Scene Analogy) as within-subject factors (Figure 13). This analysis showed a significant interaction between the Type of Stimulus and Task ($F(4,188)=52.7$; $p<.001$; $\eta^2_p=.528$), but no triple interaction between Type of Stimulus, Task, and Age.

We ran planned comparisons analyses on these data. Concerning fixations on B and C, it revealed that C was fixated more than the mean fixation of other types of stimuli in the Within-Context A:B::C:? task ($F(1,47)=37.9$; $p<.001$; $\eta^2_p=.446$), and that B was fixated longer than the mean rate of fixation of other stimuli ($F(1,47)=104.9$; $p<.001$; $\eta^2_p=.691$). The rate of fixation on B was also higher in the Scene Analogy task than in the Within-Context A:B::C:? task ($F(1,47)=133.5$; $p<.001$; $\eta^2_p=.740$), and the reverse pattern for C ($F(1,47)=48.4$; $p<.001$; $\eta^2_p=.507$), as predicted. Thus, goals affected differentially attention toward these stimuli in the two tasks. There was also a significant difference between fixations of Dis in the two tasks ($F(1,47)=9.4$; $p=.004$; $\eta^2_p=.167$). This confirms that the distractor caught the attention of participants in the Within-Context A:B::C:? task more than in the Scene Analogy task, in which it was not related to the goals of the task. In relation to our prediction about differences of fixation on Dis at different developmental times, a significant difference was found between overall fixations on Dis between children and adults ($F(1,47)=17.5$; $p<.001$; $\eta^2_p=.271$), and between Dis fixations in children and adults in the A:B::C:? task specifically ($F(1,47)=8.3$; $p=.006$; $\eta^2_p=.150$), which confirmed a developmental trend toward a better inhibition of the information from the distractor. In relation to our prediction about fixations on A and B between age groups in the A:B::C:? task, planned comparisons did not reveal any significant difference between age groups in their fixations of A ($F(1,47)=.6$; $p=.442$; $\eta^2_p=.013$) or B ($F(1,47)=.4$; $p=.507$; $\eta^2_p=.008$). Thus, part of previous differences between adults and children in the A:B::C:? task was not reproduced.

Next, we tested our predictions about AB and CT being preferred over AC and BT saccades by participants, and tasks' goals modulating BT and CDis saccades differentially, about age modulating the rate of BT saccades in the Scene Analogy task and of AB saccades in the Within-Context A:B::C:? task, because of a difficulty for children to maintain the main goal of these tasks. We also tested our predictions about the developmental trend toward a better inhibition of saccades involving the distractor (i.e., CDis saccades) in the Within-Context A:B::C:? task. We thus examined the above-mentioned saccades (Figure 14, top panel), using a three-way mixed ANOVA with Age (6-to-7-year-olds, adults) as a between-subject factor, and Transition (AB, AC, BT, CT, CDis) and Task (Scene Analogy, Within-Context A:B::C:?) as within-subject factors. This ANOVA showed a significant interaction between Task and Transition ($F(4,188)=21.5$; $p<.001$; $\eta^2_p=.313$), and between Task, Transition, and Age ($F(4,188)=4.1$; $p=.003$; $\eta^2_p=.080$).



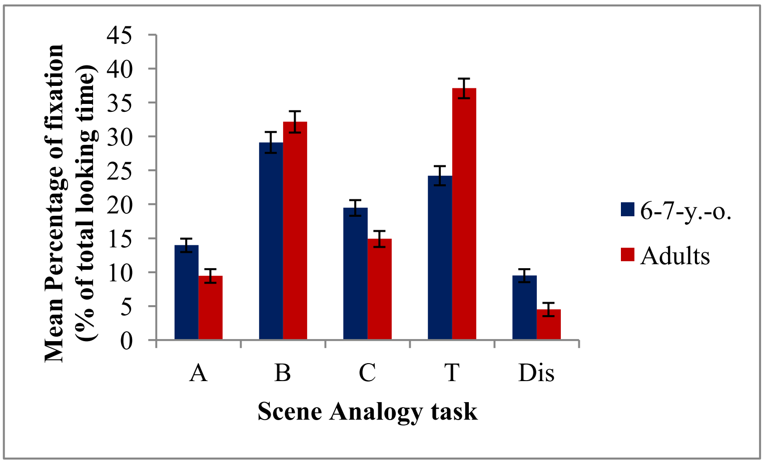


Figure 13: Children's and adults' mean percentage of fixation of each stimulus in the Within-Context A:B::C:? task (upper panel) and in the Scene Analogy task (lower panel) (error bars represent SEM).

Planned comparisons showed that AB and CT saccades were preferred over AC and BT saccades in the Within-Context A:B::C:? task ($F(1,47)=741.1$; $p<.001$; $\eta^2_p=.940$), and in the Scene Analogy Task ($F(1,47)=95.0$; $p<.001$; $\eta^2_p=.669$). A difference in the rate of BT saccades existed between the two tasks ($F(1,47)=63.8$; $p<.001$; $\eta^2_p=.576$) and between the two age groups in the Scene Analogy task ($F(1,47)=14.6$; $p<.001$; $\eta^2_p=.237$), but not between AB saccades between children and adults in the Within-Context A:B::C:? task ($F(1,47)=2.0$; $p=.160$; $\eta^2_p=.041$). These results confirmed that the goals of the task modulated the rate of BT saccades, and that maintaining the main goal of the task was more difficult for children, at least in the Scene Analogy task. The difference between rates of CDis saccades in children and adults in the Within-Context A:B::C:? task was not significant, thus contradicting our prediction of a higher rate of CDis saccades in children than in adults in this task due to lower inhibition abilities in the younger group than in the older.

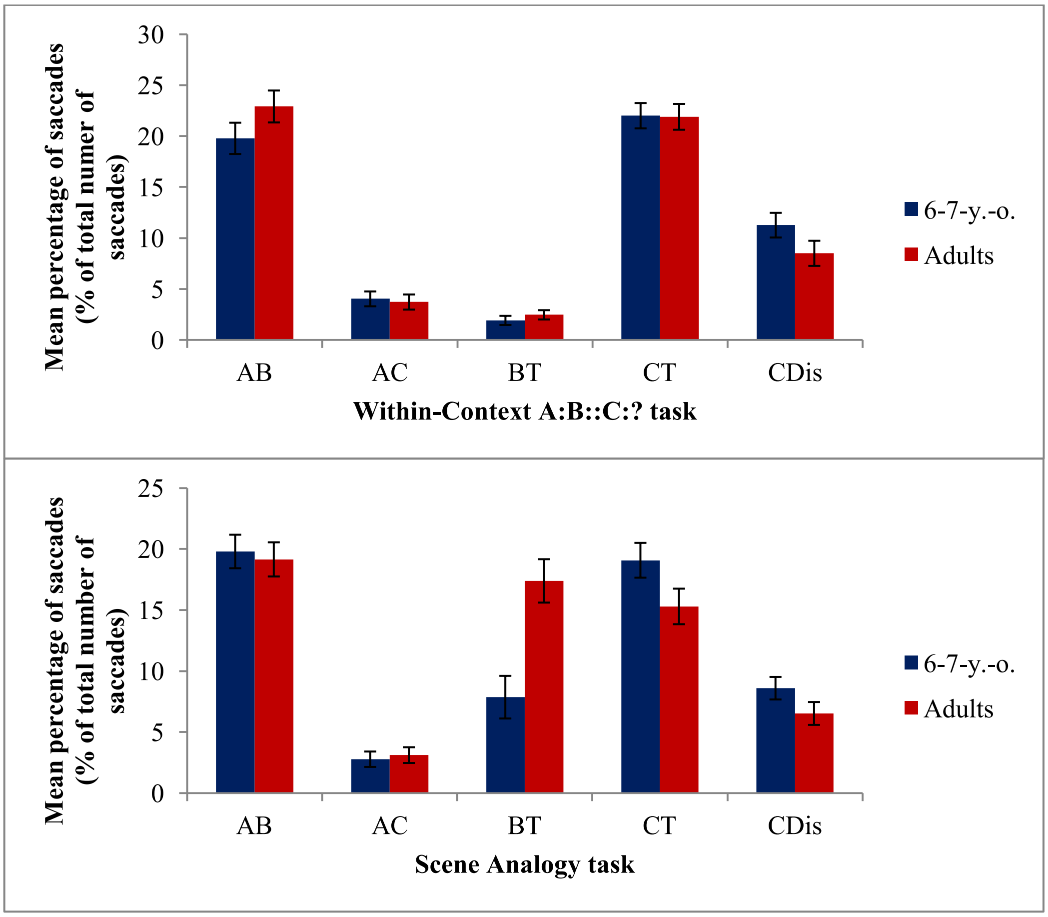


Figure 14: Children's and adults' mean percentage of each saccade in the Within-Context A:B::C:? (upper panel) and the Scene Analogy (lower panel) tasks (error bars represent SEM).

III.d. Discussion

Our hypotheses for this experiment were a difference between the goals of the two tasks compared affecting visual strategies of participants, and the developmental differences in the ability to maintain goal provoking fewer eye movement patterns linked to the goals of the task and more relational errors in children in comparison to adults. We also hypothesized that distractors would be harder to inhibit in the A:B::C:? task, due to the relevance of the distractors to the main goal of this task, than in the Scene Analogy task in which the distractors were not relevant, even partly, to the goals. Finally we hypothesized a developmental trend toward a better inhibition of distractor information.

The results we obtained suggest that the two tasks, although both testing analogical reasoning, might not be equivalent in terms of strategies and processes involved in their solution. The difference between the two tasks compared in terms of goals was confirmed by our results, showing that visual strategies differed between the Scene Analogy task and the Within-Context A:B::C:? task. Indeed the first one elicited globally more fixations on B, and more saccades between B and T, the two goal objects of this task. On the contrary, the A:B::C:? task elicited more C fixations in participants. These results indeed suggest that participants adapted their visual strategies to the different goals of the tasks in terms of emphasized constraints on the solution. These differences between tasks are successfully predicted by the Path-Mapping Theory.

Our predictions concerning the maturation of goal maintenance being involved in the development of analogical reasoning were partially borne out. Indeed, we observed fewer eye movement patterns related to goals, i.e., saccade between the item with an arrow and its corresponding element in terms of roles in the target domain, and more relational errors in children than in adults in the Scene Analogy task. However the prediction concerning goal maintenance development in the A:B::C:? task (i.e., lower AB saccades rate and A and B fixation percentages in children than in adults) were not found. These results are different from those obtained by Thibaut et al. (2011; see also Thibaut & French, submitted). These differences can be explained in several ways. A plausible explanation could be that the fact of seeing different tasks made children more aware of the necessity of the relational similarity between the two domains compared. A second hypothesis could be that the presentation of the problems in scenes influenced positively their attention toward relational information in both domains. Indeed, presentation of scenes might induce participants to be more focused on relations between elements than when presented in separated frames (Humphreys et al., 2010). This might explain the decrease in contrast between the two age groups, with children being more adult-like in their visual strategy when using scenes than when using separated pictures.

Concerning our hypothesis of a difference between distractors' ability to catch participants attention, the results show that the distractor is less distracting in the Scene Analogy task than in the A:B::C:? task, which is supported by lower distractor error rates, lower fixation of Dis and lower number of saccades involving Dis (i.e., CDis and TDis) in the former than in the latter. This can easily be explained by the framework explained above, as the distractor, even though resembling the B picture, obviously do not play the same role in the target domain as its twin picture in the source domain. Thus, the effect of distractors in the analogical tasks might be due to their relation with the main goal of the tasks.

Finally, in relation to our hypothesis that inhibition maturation might at least partly explain analogical reasoning development, we indeed observed predicted differences between the two age groups. Children were more prone to make distractor errors than adults, and had lower performances in the A:B::C:? task than adults. They also looked longer at distractors than adults overall. However, our prediction of children making more CDis saccades than adults in the A:B::C:? task was not confirmed. These results suggest that children's attention was more attracted by distractors than adult's, and thus failed to inhibit to give it as an answer, which resulted in more errors from them than from adults.

As some differences observed between adults and children, previously observed by Thibaut et al. (2011), were not observed in our results, we decided to test the hypothesis we envisaged for this difference in results (i.e., that the mode of presentation of the A:B::C:? task might influence positively children's analogical reasoning by making them focus more on the relational information). To achieve this goal, in the next Experiment, we compared the two tasks presented in this chapter with the Standard A:B::C:? task with separated elements.

IV. Experiment 3: Comparison of visual strategies elicited by scene analogy, scene-oriented A:B::C:? and standard A:B::C:? task

IV.a. Objectives and hypotheses

The objectives of this experiment were articulated around five axes: differences in goal specificity between tasks, developmental differences in the ability to maintain these goals, difference in the relevance of distractors to the goal of the tasks, developmental differences in inhibition abilities, and differences between tasks due to the presentation format (i.e., elements presented in scenes or separated). It was also designed to reproduce the results obtained by Thibaut et al. (2011) in the exact same task they used (i.e., an A:B::C:? task presented with separate elements), and compare them to the scene-oriented tasks we used in the previous experiments of the present chapter. The precedent experiment suggested differences between these two tasks (i.e., the Within-Context A:B::C:? and Scene Analogy tasks) and the task used by Thibaut et al. (2011). These differences might be explained by the presentation of stimuli in scenes, as it has been shown that this presentation format enhances attention toward relational information between the elements composing the scenes (Humphreys et al., 2010). This change in attention might be reflected by the visual strategies used by participants (and especially in the saccades between objects within domains), but also by participants' behavioral data (i.e., response accuracy and error rates), as these types of problems might be simpler than Standard A:B::C:? trials. Indeed, this attention toward relations intrinsically triggered by the presentation of the problems as scenes might help children resolve analogical reasoning problems, as this cognitive ability basically rely on relational comparison and integration (Gentner, 1983).

Relative to the first axis, i.e., differences of goals between the Scene Analogy and A:B::C:? tasks, we expected to reproduce results from Experiment 2 of this chapter (higher rates of fixation of B in the Scene Analogy and higher rates of fixation of C in the Within-Context A:B::C:? task, as well as a significant difference between these tasks in the rates of fixation of these two stimuli, and a higher rate of AB and CT than AC and BT saccades in both tasks, and of BT saccades in the Scene Analogy task than in the A:B::C:? task). We also expected that these differences generalized to the comparison between the Scene Analogy task with the Standard A:B::C:? task which shared the same goals as the Within-Context A:B::C:? task. Thus, we expected higher rates of fixation of B in the Scene Analogy task than in the Standard A:B::C:? task, and the reverse pattern for C. We also expected BT saccades to be more numerous in the Scene Analogy task than in the Standard A:B::C:? task.

The second axis postulates a developmental trend toward a better ability to maintain goals of the task as a factor in analogical reasoning development. Thus, we also expected to reproduce the results specific to this hypothesis found in Experiment 1 and 2. We should find a greater number of relational errors in children than in adults in the Scene Analogy task, the only one to allow this kind of errors. We should also observe a difference in the number of BT saccades, which are used to align and compare the roles of the goal objects in the Scene Analogy task, and reproduce results from Thibaut, French, Missault, et al. (2011) relative to this developmental hypothesis, i.e., lower rates of fixation of A and B, and lower rates of saccades between these pictures in children than in adults in the Standard A:B::C:? task.

Relative to the power of distractors to catch attention in the different tasks, in link to their relation to the goals of the task, we expected that related-to-C distractors would catch participants' attention more, and that distractor errors would be more frequent, in the Within-Context A:B::C:? task than in the Scene Analogy task, as observed in Experiment 2. We expected these differences to be observed between the Standard A:B::C:? and the Scene Analogy task too, as the goals of the two types of A:B::C:? tasks are the same.

The fourth axis predicted developmental differences in the ability to inhibit information from distractors. Thus, the previously observed differences in response accuracy and number of distractor errors between adults and children should be observed again, along with the differences in overall fixation rate of distractors, as well as in the specific Within-Context A:B::C:? task. This difference between adults and children fixations should also be found in the Standard A:B::C:? task, as related-to-C distractors should efficiently catch participants' attention.

As mentioned above, the presentation of the elements composing the domains compared (in scenes or separated) might influence participants' visual strategies, as scenes elicit attentional focus toward relations over objects (Humphreys et al., 2010). Hence, we expected more intra-domain saccades in the two scene-oriented tasks (i.e., the Scene Analogy task and the Within-Context A:B::C:? task) than in the Standard A::B:C:? task. As this attention toward relations is crucial when reasoning by analogy, we hypothesized that children would have better scores in the two scene-oriented tasks than in the Standard A:B::C:? task too. The corollary would be that they would make less distractor errors in the Within-Context A:B::C:? task than in the Standard A:B::C:? task.

To achieve these goals, we used an Age (6-7-year-olds, Adults) x Task (Scene Analogy, Standard A:B::C:?, Within-Context A:B::C:?) design, with Age as a between-subject factor and Task as a within-subject factor. The Scene Analogy task was a replication of the tasks of the two previous experiments with a slight difference due. We used related-to-C distractors, which made the distractors equivalent to the distractors in the two other tasks. Response accuracy, reaction times and eye movements were recorded.

IV.b. Methods

Participants

Subjects were 20 adults (14 females, 6 males; mean age=20.4 years; SD=2.21; range: from 17 to 27 years), University of Burgundy student and 26 6-to-7-year-olds (16 females, 10 males; mean age=79.5 months; SD=3.6; range: from 73 to 84 months). For children, parents' informed consent was required. Adults and children participated voluntarily to the task.

Materials

Three tasks, each composed of three training trials and four experimental trials, constituted the experiment (see Figure 15). The first task was a scene analogy problem task, the second a standard A:B::C:? task and the third an A:B::C:? task with the items composing the problems put within a context. Each problem of each task was composed of 7 black and white line drawings. The tasks were presented sequentially and their order was counterbalanced: the 6 possible orders were used uniformly across subjects. The order of the trials within each task was random.

In the Scene Analogy task (Figure 15a), the pictures were based on materials from Experiment 1 except for the distractor that was chosen to be semantically (and not perceptually) related to one member of the relation in the bottom picture, and were presented in the same way as in Experiment 1.

In the Standard A:B::C:? trials, the A, B, C drawings were presented at the top along with a black empty square symbolizing the place where the solution should go. The four remaining pictures (T, Dis and two U) were presented at the bottom of the screen (Figure 15b). The size of each picture was 200x195 pixels. The reason the pictures were not totally aligned in two rows was that we wanted to minimize the overlap of different saccades of participant's eyes between the different pictures. Each Picture was presented in a black frame and an eighth black frame was presented at the right end of the superior half of the screen to symbolize were the answer should go.

The Within-Context A:B::C:? task was constituted of pictures used in Experiment 2. These pictures were presented in the same way as the previous experiment.

The tasks were displayed on a Tobii T120 eye-tracker with a 1024x768 screen resolution using an E-Prime software (version 2.8.0.22) embedded in a Tobii Studio (version

2.1.12) procedure to record participants' scanpaths. Statistics were executed with the help of Statistica 8.

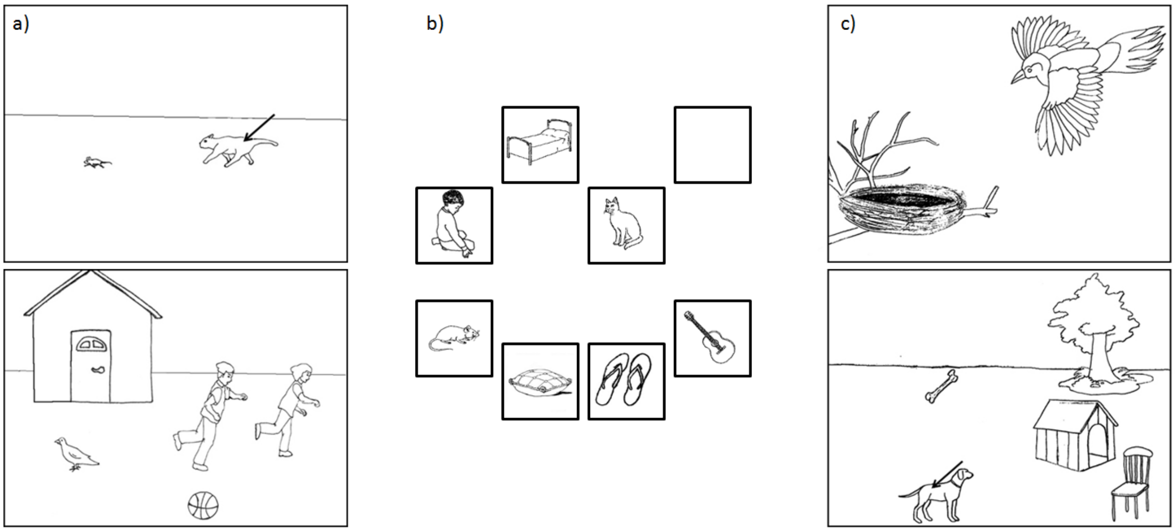


Figure 15: Presentation of the three tasks used for this experiment: a) scene analogy task, b) standard A:B::C:? task, c) Within-Context A:B::C:? task.

Procedure

Children were tested in a quiet room in their schools and adults in an experimental box at the University of Burgundy. Participants were tested one at the time.

The controls were carried out in the same way as the controls in the previous experiment. The first tasks was administered in the same way as the Scene Analogy Task in Experiment 2.The Standard and Within-Context A:B::C:? tasks were administered as the Within-Context A:B::C:? task in Experiment 2 of this chapter.

IV.c. Results

Overall, more than 99% of the stimuli were recognized in the first phase of the procedure. We excluded for further analysis 1% of the trials because of a lack of knowledge of the relation in either of the two domains composing the analogical problems. Fifteen percent of the trials were excluded of the eye-tracking analysis because of more than 50% of the eye movement data missing. It resulted in 3 6-to-7-year-olds not having any data in one task. They were excluded of the statistical analyses implying these tasks.

Behavioral results

To test predicted differences between the scene-oriented tasks and the Standard A:B::C:? task and between adults and children, we ran a two-way mixed-ANOVA on response accuracy with Age (6-to-7-year-old; Adults) as a between-subject factor, and Type of Task (Scene Analogy, Standard A:B::C:?, Within-Context A:B::C:?) as within-subject factor (Figure 16). It showed significant main effects of Age ($F(1,44)=44.3$; $p<.001$; $\eta^2_p=.502$), of Type of Task ($F(2,88)=7.201$; $p=.001$; $\eta^2_p=.141$), and a significant interaction between these two factors ($F(2,88)=7.6$; $p<.001$; $\eta^2_p=.148$). The main effect of age showing that children had lower performances than adults partly confirms our hypothesis of a development of inhibition and goal management contributing to the development of analogical reasoning. A planned comparison confirmed that scene-oriented problems were better resolved than the Standard A:B::C:? problems ($F(1,44)=33.3$; $p<.001$; $\eta^2_p=.431$), which is coherent with our hypothesis that presenting problems in scenes might help children to solve analogical reasoning problems.

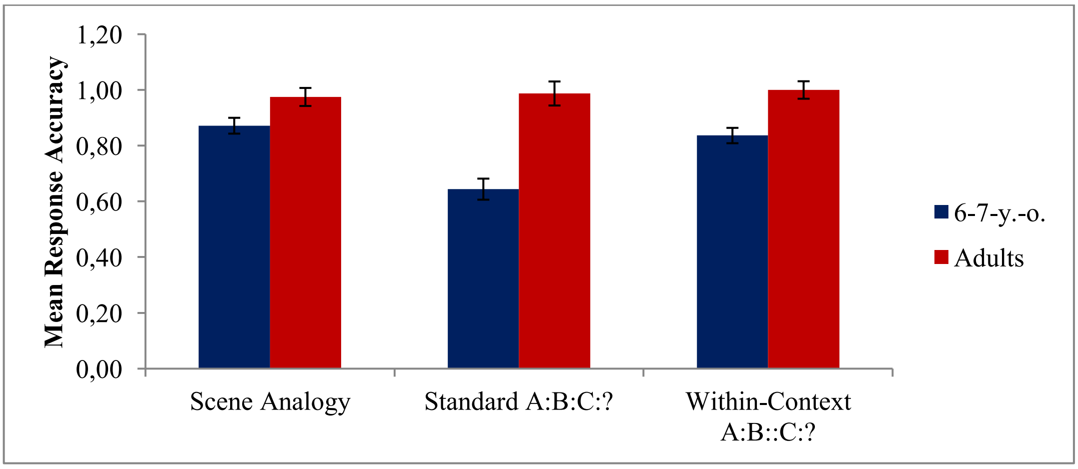


Figure 16: Mean Response Accuracy of children and adults in the three tasks (Error bars indicate SEM).

In order to reveal differences due to different inhibition maturity in our two age groups, as well as the fact that the different presentations induced behavioral differences, and that distractors differing in their relation to goals would catch participants' attention differently, we also ran the above-mentioned ANOVA design on the Number of Distractor Errors (Figure 17). This analysis revealed significant main effects of Age ($F(1,44)=37.9$; $p<.001$; $\eta^2_p=.463$) and Task ($F(2,88)=17.1$, $p<.001$; $\eta^2_p=.280$), and a significant interaction between the two factors ($F(2,88)=16.6$; $p<.001$; $\eta^2_p=.274$). The main effect of Age is coherent with our hypothesis of inhibition development affecting the development of analogical reasoning. Planned comparisons between Scene Analogy distractor error rates and the two other tasks confirmed that the rate of these errors was lower in the former than in the two A:B::C:? tasks ($F(1,44)=26.6$; $p<.001$; $\eta^2_p=.377$). This confirmed that the distractor was less salient for participants in the Scene Analogy task than in the two other tasks. We also compared the Within-Context and the Standard A:B::C:? task. It confirmed that distractor errors were less frequent in the former than in the latter ($F(1,44)=11.8$; $p=.001$; $\eta^2_p=.211$), which was coherent with the difference between presentations we hypothesized.

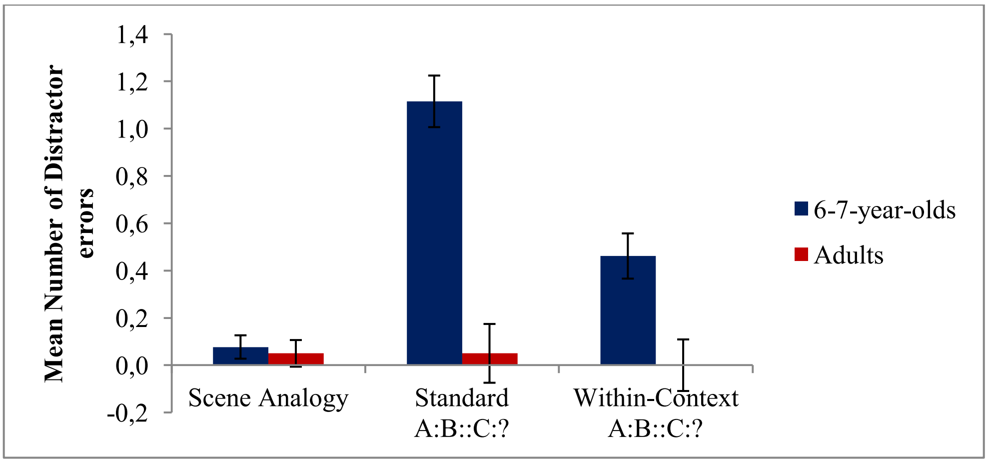


Figure 17: Mean Number of Distractor errors in adults and children (Error bars represent SEM).

To test our hypothesis about goal maintenance development partly, we analyzed the difference in number of relational errors between children and adults in the Scene Analogy task, running a two-sample independent t-test (Figure 18). It revealed a significant difference, with greater number of relational errors in children than in adults ($t(44)=2.3$; $p=.027$; $\eta^2_p=.106$).

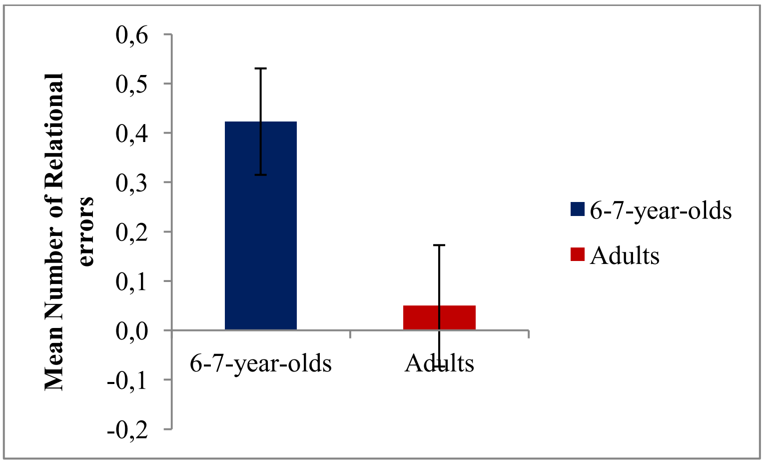


Figure 18: Mean Number of Relational errors in children and adults (Error bars represent SEM).

We ran the same ANOVA analysis on reaction times (see also Figure 19). It revealed a significant effect of Age ($F(1,44)=44.3$; $p<.001$; $\eta^2_p=.502$). Neither Type of Task ($F(2,88)=.668$; $p=.515$; $\eta^2_p=.015$) nor the interaction between Age and Type of Task ($F(2,88)=.468$; $p=.628$; $\eta^2_p=.011$) reached significance. Due to the main effect of age, we used percentage of total fixation and of total number of saccades as measure of eye movements subsequently.

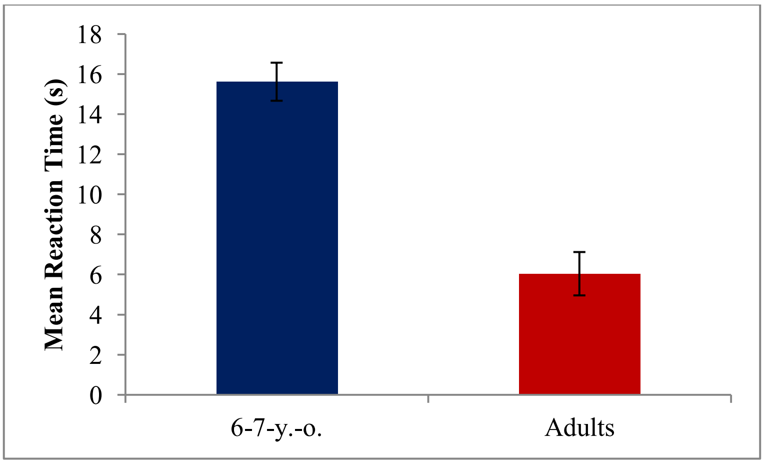


Figure 19: Mean reaction time of children and adults in the task

Visual Strategies

Regarding our hypotheses about fixations being influenced by the goal specificity of the tasks, the relevance to the goals of the distractors, the ability to maintain goals, and inhibition abilities, we analyzed fixation durations of the stimuli, running a two-way mixed ANOVA with Age (6-to-7-year-olds, adults) as a between-subject factor, and Type of Stimulus (A, B, C, T, Dis) and Task (Scene Analogy, Standard A:B::C:?, Within-Context A:B::C:?) as within-subject factors (Figure 20). There was significant interactions between Age and Type of Stimulus ($F(4,164)=7.6$; $p<.001$; $\eta^2_p=.156$), between Task and Type of Stimulus ($F(8,328)=17.1$; $p<.001$; $\eta^2_p=.294$) but not between the three factors ($F(8,328)=1.9$; $p=.063$; $\eta^2_p=.044$).

We tested our assumptions about task specificity in terms of goals with planned comparisons between rates of fixation of B and C, and between these stimuli and the others within each task. These comparisons confirmed that B was fixated ore than the other stimuli in the Scene Analogy task ($F(1,41)=79.6$; $p<.001$; $\eta^2_p=.660$), and C in the Standard and the Within-Context A:B::C:? task (respectively: $F(1,41)=12.0$; $p=.001$; $\eta^2_p=.226$; $F(1,41)=8.1$; $p=.007$; $\eta^2_p=.165$). and that B was fixated longer in the Scene Analogy task than in the two A:B::C:? tasks ($F(1,41)=63.9$; $p<.001$; $\eta^2_p=.609$), but did not show that C was fixated longer in A:B::C:? tasks than in the Scene Analogy task ($F(1,41)=2.86$; $p<.010$; $\eta^2_p=.065$). Concerning the power of distractors, we compared the fixation rate of distractors in the two A:B::C:? tasks to this rate in the Scene Analogy task. Planned comparisons confirmed that distractor was fixated more in the two A:B::C:? tasks than in the Scene Analogy task ($F(1,41)=130.5$; $p<.001$; $\eta^2_p=.761$). We also tested our hypothesis about the role of the development of inhibition in analogical reasoning development. Dis was generally looked longer by children than adults ($F(1,41)=18.5$; $p<.001$; $\eta^2_p=.311$), and especially in the two A:B::C:? tasks ($F(1,41)=18.2$; $p<.001$; $\eta^2_p=.307$). In relation of our hypothesis of goal maintenance development in analogical reasoning, we tested the difference between the rate of fixation of A and B between children and adults in the Standard A:B::C:? task. It revealed that A was not looked at significantly longer in adults than in children ($F(1,41)=1.1$; $p=.306$; $\eta^2_p=.026$) but that B was ($F(1,41)=5.9$; $p=.020$; $\eta^2_p=.126$).

To test the predictions of the influence of the different factors mentioned on saccades in the different task, we then turned to the analysis of saccades (Figure 21). First, we examined saccade patterns using a two-way mixed ANOVA with Age (6-to-7-year-olds, Adults) as a

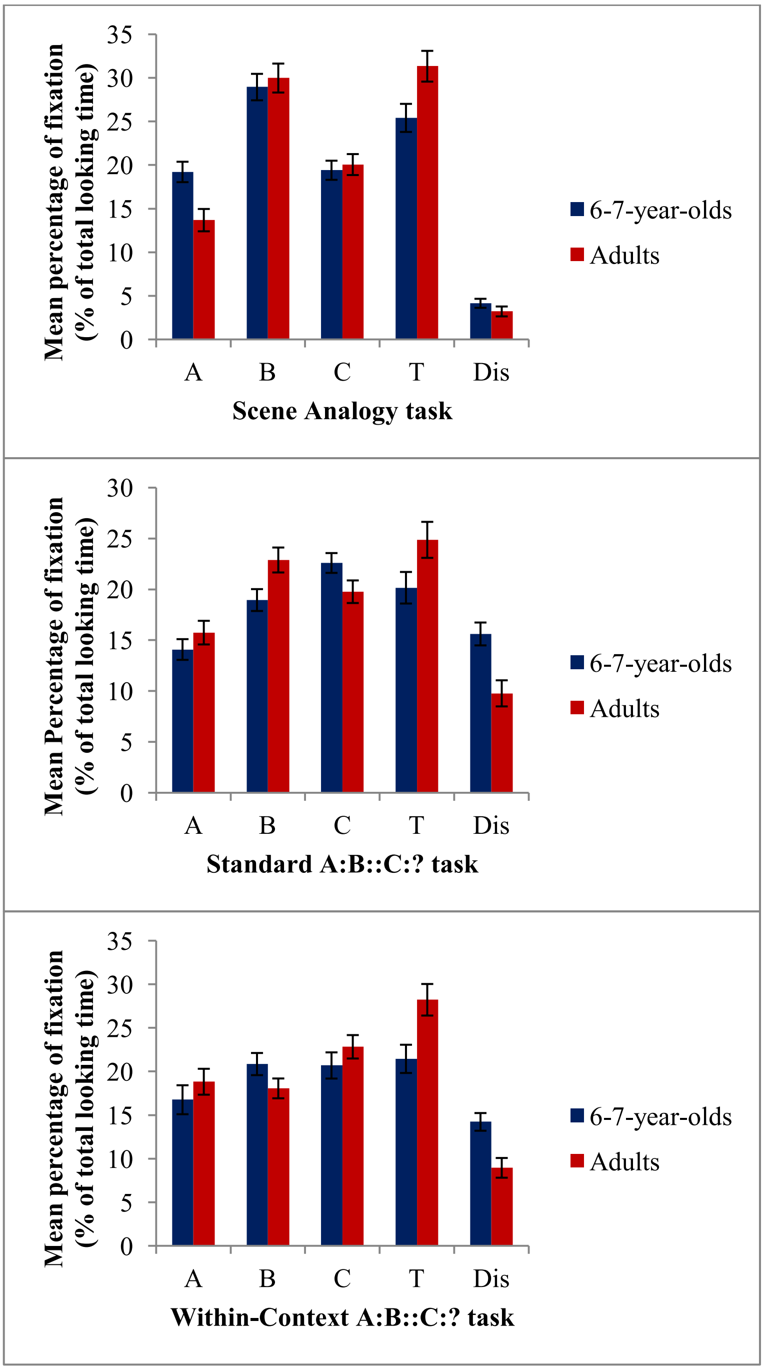


Figure 20: Mean percentage of fixation of each stimulus in children and adults in the Scene Analogy (upper panel), the Standard A:B::C:? (middle panel), and the Within-Context A:B::C:? (lower panel) tasks (Error bars indicate SEM).

between-subject factor, and Transition (AB, AC, BT, CT, CDis, TDis, TU, DisU) and Task (Scene Analogy, Standard A:B::C:?, Within-Context A:B::C:?) as within-subject factors. It revealed a significant interaction between Transition and Task ($F(14,574)=39.2$; $p<.001$; $\eta^2_p=.489$), and between the three factors ($F(14,574)=1.8$; $p=.035$; $\eta^2_p=.042$).

We first tested our hypothesis about the rates of AB and CT saccades being greater than the rates of AC and BT saccades in the three tasks. It was confirmed in the three tasks (Scene Analogy: $F(1,41)=560$; $p<.001$; $\eta^2_p=.932$; Standard A:B::C:?: $F(1,41)=305.1$; $p<.001$; $\eta^2_p=.882$; Within-Context A:B::C:?: $F(1,41)=272.4$; $p<.001$; $\eta^2_p=.869$).We then tested our hypothesis about the specificity of BT saccades in the Scene Analogy task with a planned comparison. It revealed a significantly higher rate of BT saccades in the Scene Analogy task than in the two A:B::C:? tasks ($F(1,41)=34.5$; $p<.001$; $\eta^2_p=.457$). We also tested the hypothesis about goal maintenance development with the AB saccades in the Standard A:B::C:? task, and BT saccades in the Scene Analogy task. It revealed no significant difference between the rates of AB saccades between adults and children in the Standard A:B::C:? task ($F(1,41)=.5$; $p=.467$; $\eta^2_p=.012$) but a higher rate of BT saccades in adults than in children in the Scene Analogy task ($F(1,41)=8.1$; $p=.007$; $\eta^2_p=.165$), thus partially confirming our hypothesis. We also tested the hypothesis of more frequent intra-domain saccades in the scene-oriented tasks than in the Standard A:B::C:? task. Planned comparison revealed significantly more intra-domain saccades in the scene-oriented tasks than in the separated format ($F(1,41)=24.3$; $p<.001$; $\eta^2_p=.372$), thus confirming our hypothesis.

IV.d. Discussion

The study of visual strategies and behavioral data in the three different tasks used was designed to several hypotheses. First we wanted to know if the presentation of problems in scenes could help participants, and especially children to focus on the relational information, and thus improve their performances in such problems. We also furthered our explorations of the relation between tasks goals and visual strategies, and the influence of the development of the ability to maintain goals on analogical reasoning, as well as the link between the efficiency of distractors and their relations to the goals of the task. In addition to this, we also studied the link between the development of inhibition abilities and analogical reasoning.

The results of the previous experiments concerning the goal specificity of analogical reasoning tasks were reproduced fairly well and extended to the Standard A:B::C:? task. The Scene Analogy task led participants to focus more on B than the two A:B::C:? tasks, and generated more BT saccades, saccades related to the main goal of the task. However the greater focus on C in the two A:B::C:? tasks than in the Scene Analogy task was not reproduced. These results suggest that indeed the two types of analogical reasoning tasks differ in their goals and that participants adapt their strategies to these different goals. This is predicted only by the Path-Mapping Theory as explained above.

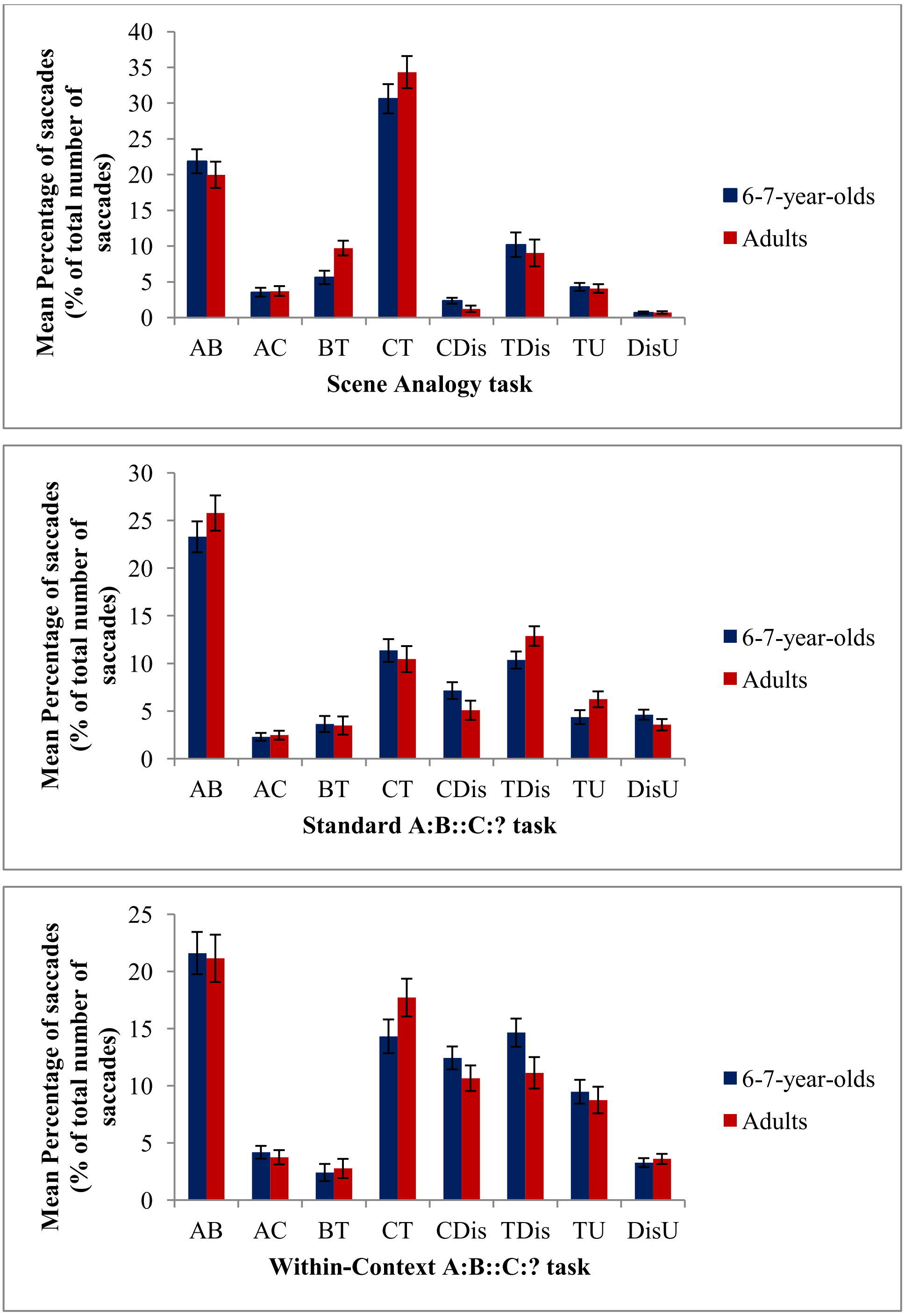


Figure 21: Mean Percentage of each saccade in the Scene Analogy (upper panel), Standard A:B::C:? (middle panel), and Within-Context A:B::C:? (lower panel) task (Error bars represent SEM).

The results linked to the development of goal maintenance abilities were not conclusive in the Standard A:B::C:? task. We did not reproduce previous findings observed by Thibaut, French, Missault et al. (2011) about children's lower consideration of the AB pair in comparison to adults. This experiment eliminates the possibility of these differences between our observations and theirs to be due to differences in the presentations of the task, as this possibility was left open by the precedent experiment. This could be that using different tasks enhanced children's understanding of the constraints on the solution and the usefulness of the AB pair in finding the solution. This hypothesis remains to be tested. However, the results about the development of goal maintenance previously observed in the Scene Analogy task were observed again: children made more relational errors than adults, and made less BT saccades than them.

The findings about the link between the power of distractors and their link to the goals of the task were extended to the Standard A:B::C:? task. The distractors were chosen more often, and were fixated longer in the two A:B::C:? tasks than in the Scene Analogy task. Inhibition abilities seemed to modulate analogical reasoning. Children made more distractor errors, had lower scores, and fixated the distractors longer than adults, especially in the tasks were the distractors played their role. The change of distractors for related-to-C distractors in the Scene Analogy task has lowered the difference between children and adults in terms of distractor fixations and errors, as in scores. This can be explained easily by the explicit focus of tasks in terms of similarity of the roles of B and the solution. Even though the distractors were semantically related to C, they were not related in roles. Thus, one would predict giving an obvious role of the distractors in the scene, like Richland and collaborators (2006) did with the addition of a distractor that was related to C with the opposite relation, might lead to more distractor errors in this kind of task. We show in chapter III that even adults are distracted by this kind of “opposite-relation” distractors in an A:B::C:? task. However, Richland et al.’s study (2006), due to the ambiguity of the mapping intrinsic to the task cannot disambiguate errors of mapping (i.e. what we called relational errors) from distractor errors due to the more sustained attention of children on something that has a role played in the target domain, whatever this role is. The presence of this kind of errors in adults even when the mapping is obvious (see chapter III) might be an indirect argument in favor of a distractive effect due to the presence of an element having a role, even though irrelevant, in the target domain. However this prediction would be easy to test directly in children with an equivalent scene analogy task, with distractors playing an irrelevant role in relation with C, and asks the question of what makes a distractor more distractive in analogical reasoning tasks.

Finally, concerning the differences between scene-oriented problems and problems displaying elements in separate frames, the first seemed to elicit more intra-domain saccades which is coherent with the view that scenes increase attention toward relations. The predicted interactions of response accuracy and of number of distractor errors between the within-context and standard A:B::C:? task was also present. Thus, the within-context task, although equivalent in terms of instructions and focus, might alleviate some difficulty related to the presence of distractors, by the presentation in scene. This might be due to the scene enhancing attention toward relational information (Humphreys et al., 2010).

V. General discussion

One important finding of this chapter is the fact that we observed a difference between the ability of children to answer correctly the scene-oriented problems and problems with separated elements. This finding was related to a higher number of comparisons between the objects of the same domain in the eye-tracking data. We explain this observation by recent findings showing that displaying objects in meaningful scenes makes participants focus more on the relations between the objects (see Humphreys et al. (2010) for a review). These findings can be explained by the fact that meaningful scenes orient attention toward relations. This attentional effect can lower the cost of encoding the target domain relations, and decreases the interference of the main goal of the task (i.e., finding what goes with C) with this encoding process (Blaye, Glady, & Thibaut, 2013).

In these three experiments, we observed reliable findings concerning the visual strategies used to solve the three tasks we gave to our participants. The A:B::C:? tasks were solved with a majority of AB and CT saccades which are likely to be attempts by the participants to encode the relations between these terms (Thibaut, French, Missault, et al., 2011, see also Thibaut and French (submitted)). These relational extractions were common with the scene analogy task. However, specific to the proportional A:B::C:? task (either in the classic or the within-context format) is the comparison of the different options that are related to C (i.e., T and Dis). The extensive comparison of these objects might be related to the goal of this specific task: finding something that is related to C. In chapter V, we show that the emphasis of the instructions on this goal affects younger children's ability to address the task correctly. What makes the distractor really attractive for the eye, especially for children, is its connection to this goal of the task (Yarbus, 1967). We saw that the effect of a distractor that is irrelevant to the goal of the task vanishes in the results of the scene analogy task.

In the Scene Analogy task, we did not find a need for participant to compare extensively any other pair of objects than C and T in the target domain scene. This result is accentuated by the low level of selection of distractors in this task. Hence, distractors did not have any distracting effect. This can once again be related to the emphasis of the task's instructions. In this task, participants were instructed to find what played the same role in the target picture as the one pointed at in the base picture. However, the distractors did not play any role in relations in the pictures: they were either semantically related to the action of interest for the analogical comparison, or perceptually similar to the object that was pointed at in the source picture, but were not actors of a relation. We would thus predict that a distractor being implicated in another action, thus having a role, even though not the same as the solution of the problem, would be of more interest, and/or might be chosen more often, at least by young children.

The effect of tasks goals might also be related to the difference we observed between the scores of children in our experiments and those in Richland et al.'s (2006) study. In their study, in the comparable condition (i.e., one relation, one distractor) 6-to-7-year-olds had fairly low scores (65%), when ours had between 75 and 85% of correct answers, depending on the experiment. Richland et al. (2006) observed also a great number of object matches in this age group, what we did not observe in our sample. These differences can possibly be explained by the vagueness of the instructions used: children had to find what was the same part of the pattern in the bottom picture as the one pointed to in the top picture. These instructions do not provide any clue that what has to be chosen is an object corresponding in terms of role, making the perceptual match a plausible answer.

Another interesting finding in this task was the difference in the percentages of saccades between B and T between children and adults. This saccade is directly related to the main goal of the task (i.e., finding what plays the same role in the two pictures) because it allows participants to compare the roles of these two objects in a direct manner. The observation that children rely less on this comparison in their reasoning is better apprehended when related to their greater number of relational errors when compared to adults: children might make more relational errors because they do not explicitly align the different role-fillers but only compare the relations in their similarity. Another interesting fact is that the alignment process is not exhaustive but merely focused on the tasks goals: even adult participants do not map A on C in this task. This is predicted by Salvucci & Anderson's (2001) Path-Mapping Theory in which goals affect the actions done with the material. These experiments show that this goal constraint on mapping is visible even in the perceptual, information gathering process of participants solving an analogical reasoning task. However, all the theories and models of analogical reasoning but the Path-Mapping Theory predict that the mapping is the more exhaustive it can be (that is, an analogy maker maximizes the number of object correspondences between the source and the target). The results in this chapter and the following one argues against this view, and clearly shows that participants attend to and evaluate extensively only subparts of the mapping between the two structures to be compared, subparts that are central to the task's goal while solving the task. The Path-Mapping Theory (Salvucci & Anderson, 2001) is the only one to our knowledge to allow a partial mapping between the source and the target in response of specific goals of the task.

The effect of task's goals on the behavior of children and their tendency to make less BT saccades makes the interpretation of the relational errors in Richland et al.'s (2006) study equivocal. The finding that children made more relational errors could at least partly be attributed to different, non exclusive factors other than the simple working memory load argued by the authors. For instance, it could be attributed to a lack of inhibitory process efficiency, making an attractive distractor that is related to the goal of the task (i.e., that plays any role in the bottom picture) difficult to overcome and cope with, or, even if children have enough working memory to process ternary relations, to a difficulty to align and/or to check the correspondences between the two sets.

Another recurrent finding in the experiments presented in this chapter was the difference in the effect of the distractor between children and adults in A:B::C:? tasks. Children paid systematically more attention to the distractor than adults, resulting in it being chosen more often by children than adults. In our view, this is linked to the maturation of executive functions, and especially inhibition, being involved in the development of analogical reasoning. Indeed, executive functions have been shown to develop through childhood and adolescence (see Diamond, 2013 for a review), and are determinant in participants ability to solve problems, as they have to navigate through a search space of different possibilities to find the correct solution (Thibaut et al., 2010a, 2010b). They permit participants to examine the different possibilities of the search space efficiently and not to remain stuck in the consideration of a tempting but irrelevant answer (i.e., the distractor), and to change their representation of the problem in case of an impasse being reached (i.e., the exhaustion of all solution possibilities in the search space without finding a satisfying answer).

In conclusion, the results presented in this chapter allows us to argue that different goals lead to different strategies for gathering information, and that goal is central to this process (see Spellman & Holyoak (1996) for convergent findings). The A:B::C:? task is clearly focused on the comparison of two relations in terms of similarity, which lead participants to only extract the relational information (AB and CT saccades), and compare the different possibilities in terms of that relational similarity. In any case, participants do not check the mapping between the two domains' objects explicitly in the A:B::C:? task. On the contrary, the scene analogy task is more focused on the mapping of a particular object in the source domain on a particular one in the target domain. This results in the explicit evaluation of the alignment between these two objects by adults, but not children, which explains their relational errors. However task instructions are not the sole factor to affect participants' information gathering: we showed that the presentation of stimuli in scenes affect the attention children pay to relations, especially in the target scene. This might affect their ability to reason by analogy by a better encoding and comparison of the complete relational information, this information being crucial to perform the task. These results are coherent with the demonstration by other authors of the ability of the presentation of the task to affect the way participants solved it (Keane et al., 1994). These experiments also show two strong factors in the development of analogical reasoning: the development of the ability to maintain goal while solving a task, and the ability to inhibit information irrelevant to these goals. The next chapter will show that even if these capabilities are more efficient in adults, they are still an important factor in their ability to reason by analogy.

Adults' visual strategies in complex A:B::C:? problems

Chapter III: Adult's visual strategies in complex A:B::C:? problems

I. Background

This chapter is composed of two experiments. Their goal was to assess the robustness of adults' visual strategies observed in the preceding chapter in the A:B::C:? task when the difficulty of the problems is greater than that of problems designed for children. The main goal was to manipulate the difficulty of the analogy and to assess the consequences of this manipulation on the search organization. This was a way to test the robustness of the predictions of the models confirmed in chapter II (i.e., more within- than between-domains saccades, focus on the goal objects). Indeed, it could be argued that easy analogies can be easily solved by projection of inferences from the first pair and that more difficult analogies would involve more back and forth movements. First, we tested a general factor of difficulty as assessed during pretests of the materials (Experiment 1) then we manipulated the semantic and perceptual structures of the problems (Experiment 2).

Bethell-Fox et al. (1984) showed that the difficulty of the task was found to influence visual strategies in a geometrical A:B::C:? task (see Figure 22), especially in participants with lower fluid intelligence. They observed that these participants tended to have an approach less based on the construction of an hypothesis for the solution, but consisting in eliminating answers that were not plausible. In addition to this, difficult items elicited more looks back to A and B, to spend more time on the stem of the problem longer before giving a first look to alternatives, and to look at these alternatives more often than in simple ones. The response-elimination strategy (i.e., eliminating each answer option one after the other by finding if it does not fit one of the different relations which have to be taken into account to determine the solution) observed in these trials seems to be due to participants looking for the solution they constructed before looking at the solution set, but not finding it in the solution set. Another interesting finding is that when looking first to the correct answer, participants tended to look at a lower number of alternatives than when it was an incorrect answer that was first looked at. The same was observed in ambiguous items, i.e., items in which the most obvious solution was not present in the alternatives.

Our task was a semantic, verbal analogy task, and thus, differences could be expected in the patterns of fixations and saccades due to differences between geometric and verbal analogies. Indeed, geometric analogies can have several objects serving as A terms and B terms, which have to be taken into account at the same time, when our verbal analogies only had one word corresponding to each term of the analogy. Thus, these differences of numerosity, and the related relational complexity (in the sense of Halford et al. 1998) might influence differentially the visual strategies of participants. Indeed the complexity of our task could not be attributed to relational complexity as the number of relations between A and B and C and T was kept constant (i.e., one relation). However, we expected similar findings (i.e., more encoding of the AB pair and more comparisons between the different answer options), but due to different reasons than the load in working memory. The differences observed in the different types of trials should be due to the interaction between executive functions and the representations they work on, as the difficulty here is to represent clearly and distinguishably the relation meaning between the pairs of objects to allow a correct discrimination of the possible answers, rather than to keep active all relations between the different terms at the same time, which might explain why participants would go back on the A and B terms more often when the relations are more numerous. As we manipulated the difficulty, we expected more returns to A and B after seeing the solution set in difficult trials than in easy trials, because the relation between A and B would not be clear without seeing the solution set.

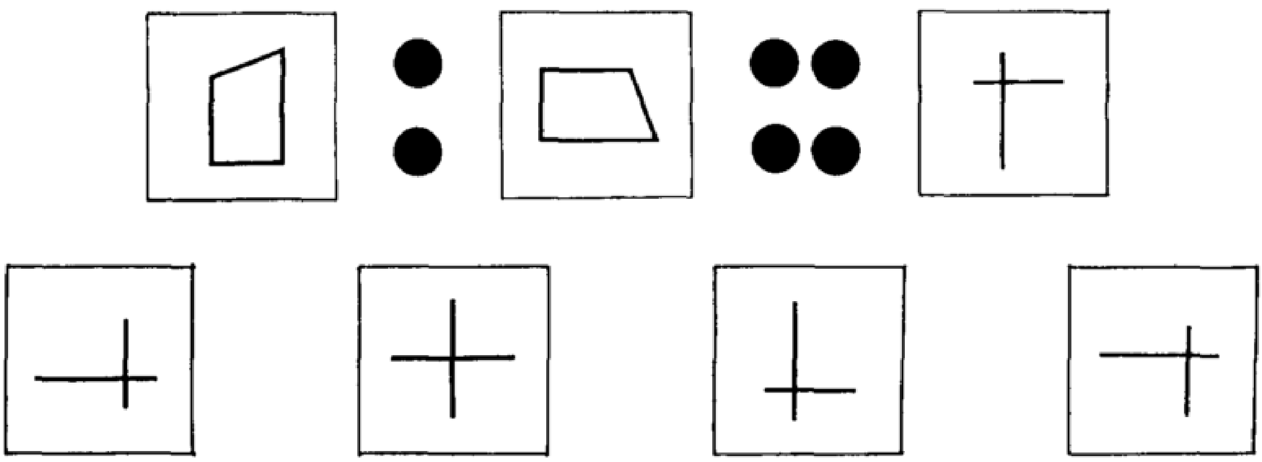


Figure 22: Sample materials from Bethell-Fox et al., 1984.

The second experiment used a different type of distractors: opposite-relation distractors (i.e., distractors that have the same relation to C as A has to B, instead of B to A). The studies presented in chapter II showed that children made relational errors (i.e., mapping errors), and that goal influenced what information was treated by participants in analogical reasoning tasks. However, relational errors were not possible so far in the A:B::C:? task, because of the absence of such a possibility in the answer options proposed in the solution set. As the goal of the A:B::C:? task is more focused on the similarity between the relations than on the mapping of the objects themselves, and as the resolution of other mapping tasks are influenced by their structure (i.e., the order of presentation of stimuli) and goals (i.e., the purpose of the mapping; Keane et al., 1994; Spellman & Holyoak, 1996), it seemed reasonable that this kind of distractors might elicit more errors than a simple related-to-C distractor. Indeed, the results described in the preceding chapter suggest that the A:B::C:? task elicit few saccades attributable to a mapping between the two domain's elements, contrary to the more mapping-based scene analogy task. Thus, the mapping of the different terms of the analogies in terms of roles in the similar relations seems not to be explicitly constructed and evaluated in the A:B::C:? task. Only the similarity between the relations inferred between the solution and C and between A and B seem to be evaluated. Another possible explanation of the absence of saccades associated with mapping one domain on the other could be that the mapping is implicitly given by the structure of the task and that participants rely on this structure, which would not lead to more errors in this case. In this second experiment, we also manipulated the direction of the task (i.e., presented from left to right; A:B::C:?, or from right to left, ?:C::B:A). This was done because this manipulation was showed effective in increasing the cognitive load of the task (Barnes & Whitely, 1981). We thus hypothesized that participants resources being already taken in the restructuration of the problem, less resources could be spent in the inhibition of such distractors, and thus that there would be more errors with the opposite-relation distractor than the simple related-to-C distractor.

II. Experiment 1: Effect of difficulty on visual strategies in the A:B::C:? task

II. a. Objectives and Hypotheses

The objective of the present experiment was to test whether adults' strategies would be modified by the difficulty of the analogical problems. So far, we only tested adults with analogies designed for children. As mentioned above, difficult problems might have an impact on participants' visual strategies used by participants (Bethell-Fox et al., 1984). For this reason, we compared Easy and Difficult conditions in a within-subject design. Easy trials were trials in which the relation between A and B, and C and T was obvious. An example of Easy trials is cow:milk::hen:?. In this example, adults do not have any difficulty to find that cows produce milk, and then to find that the solution in the different choices in the solution set is egg, as hens produce them. Difficult trials were designed not to be as straightforward as the Easy trials. Indeed, the relation between A and B was less obvious than in the former type of trials. The following problem is an example of Difficult trial: violence:activity::gloom:?. The relation between violence and activity (i.e., violence is a negative type of activity) is far from being obvious, and thus the solution (mood) would be more difficult to find.

We expected the previously observed high rates of C fixation due to the goal of the task emphasizing this term, and, because of the Path-Mapping Theory convincingly predicting what kind of visual patterns would be found in analogical reasoning tasks, and of previously observed results in the A:B::C:? task, greater rates of AB and CT saccades in comparison to AC and BT saccades.

In order to confirm our assumptions about the difficulty of the trials, in addition to Difficult trials being rated more difficult than Easy trials in pretests, Difficult trials should also elicit lower scores, more distractor errors, and longer reaction times than Easy trials.

We hypothesized that participants would engage differently their inhibition in these different types of trials. Indeed, as the relation is harder to define clearly, at least at first sight, we expected that participants would have longer fixations on the distractor overall in the Difficult than in the easy trials, and would make more CDis saccades, which are related to the encoding of the relation between these terms. These patterns of eye-movements would be related to a difficulty to engage inhibition against the information from the distractor in the difficult trials as this engagement is dependent on the recognition of a solution as irrelevant. This recognition might be harder with less clearly represented relations than with obvious relations.

Our second prediction is that participants will have to re-represent the AB pair after seeing the solution set in Difficult trials, but not in the Easy trials, making use of cognitive flexibility. Thus, we shall have overall longer fixation times on A and B, and more AB saccades in Difficult trials than in Easy ones. As the process of flexibility has an inherent dynamic nature, we should also observe differences over time. A and B fixations and AB saccades should be greater after participants saw the different answer options and compared them. This higher interest in A and B, and their relation could not be attributed to the refreshing of a great number of relations, as it was the case in the study by Bethell-Fox et al. (1984), because we used verbal analogies, thus limiting to one the number of relations between A and B which had to be taken into account at the same time to solve the problems.

II. b. Methods

Participants

Participants were 20 adults (6 males, 14 females; M=23.8 years; SD=4.2; from 17 to 35 years) who were students at the University of Burgundy. Participants were naïve to the task and participated voluntarily.

Materials

The task consisted in 22 trials (2 training trials and 20 test trials) of a verbal A:B::C:? task. The test trials were divided in two conditions: 10 were Difficult trials, and 10 were Easy trials. The 2 training trials were displayed before the 20 test trials, and the order of presentation was random.

Each trial was composed of eight words written in black ink on a white background, corresponding to the A, B, and C terms of the analogical problems, and 5 potential solutions. The solution set was composed of the Target (T), 2 related-to-C distractors (Dis), and 2 unrelated distractors (U). Each word was presented in a black frame (220x220 pixels). The A, B and C terms were presented in a row at the top of the screen along with an empty black frame were the solution should go, and the 5 words composing the solution set were displayed in a row at the bottom of the screen.

The difficulty was assessed by 12 students at the University of Burgundy. They were asked to solve the different problems and to evaluate on a 1-7 scale how difficult they found the solution of the problem was. Difficult trials were rated significantly higher (M=3.9; SD=.4; from 3.5 to 4.6) than Easy trials (M=1.2; SD=.1; from 1.1 to 1.3; two-sample related t-test: $t(22)=23.2$; $p<.001$; $\eta^2_p=.961$).

The task was presented on a Tobii T120 eye-tracker (resolution: 1024x768) with an E-Prime (version 2.8.0.22) experiment embedded in a Tobii Studio (version 2.1.12) procedure to record participants' eye-movements. Data were analyzed using a Statistica 8 software.

Procedure

The procedure used for the explanation and administration of the A:B::C:? task was identical to the one used in Experiment 3 of Chapter II, with an additional sentence by the experimenter, stating that participants should be careful about the match between the elements of the two domains.

II. c. Results

Behavioral data

To control the ability of our trials to be more or less difficult for participants, we analyzed behavioral data with bilateral paired t-tests. These analyses showed differences between Difficult and Easy trials (Figure 23). Difficult problems were solved correctly less often than Easy problems ($t(19)=4.9$; $p<.001$; $\eta^2_p=.558$) and all errors were distractor errors. In addition to this, the former were solved more slowly than the latter ($t(19)=9.92$; $p<.001$; $\eta^2_p=.838$). This confirms that Difficult trials were harder for our participants to solve than Easy trials, and suggested that the engagement of inhibition was harder in the Difficult trials. We subsequently used percentage of total fixation time and percentage of total number of fixations because of the difference in reaction times between the two conditions.

Eye movement analysis

Overall, two trials were not used for further analysis because of the number of missing points being superior to 50%. Due to the difference of reaction times between Difficult and Easy trials, we used percentage of total looking times and of total number of saccades for comparisons.

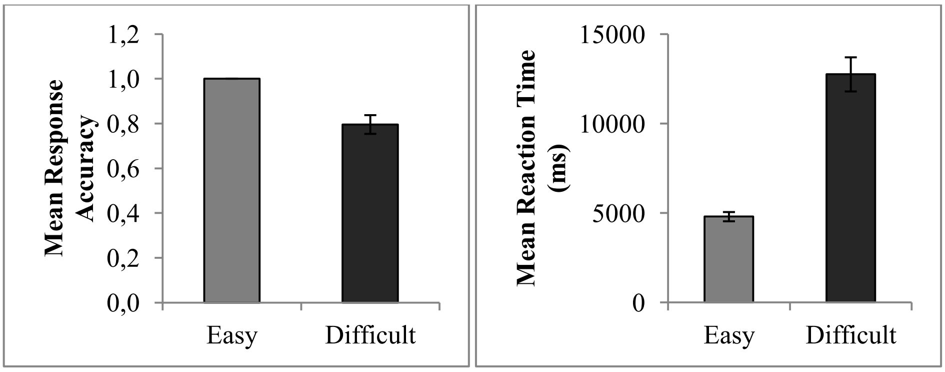


Figure 23: Mean Response Accuracy and Reaction Times in easy and difficult trials (error bars represent SEM).

Whole trial analysis

To further our analysis of the fixation patterns in Easy and Difficult trials, we ran a two-way repeated-measure ANOVA with Type of Stimulus (A, B, C, T, Dis) and Condition (Difficult, Easy) as within subject factors (Figure 24). The interaction between Condition and Type of Stimulus was significant ($F(4,76)=27.8$; $p<.001$; $\eta^2_p=.594$). Planned comparisons did not show that the mean fixation percentage of C was greater than the mean percentage of fixation of the other stimuli ($F(1,19)=1.2$; $p=.295$; $\eta^2_p=.059$). The analyses of the difference between the percentage of fixation in Easy and Difficult trials showed no significant difference for A ($F(1,19)=2.1$; $p=.161$; $\eta^2_p=.100$) and for B ($F(1,19)=.0$; $p=.861$; $\eta^2_p=.0$), but showed a significant difference for Dis ($F(1,19)=25.5$; $p<.001$; $\eta^2_p=.573$). These results partially confirmed our hypothesis about engagement of inhibition being more difficult in difficult trials, but invalidate our hypothesis about re-representation being needed for difficult trials. However, differences in the dynamics of the process might have been masked by a whole trial analyses. We will come back further to this hypothesis in the analyses between the different slices of the trials below.

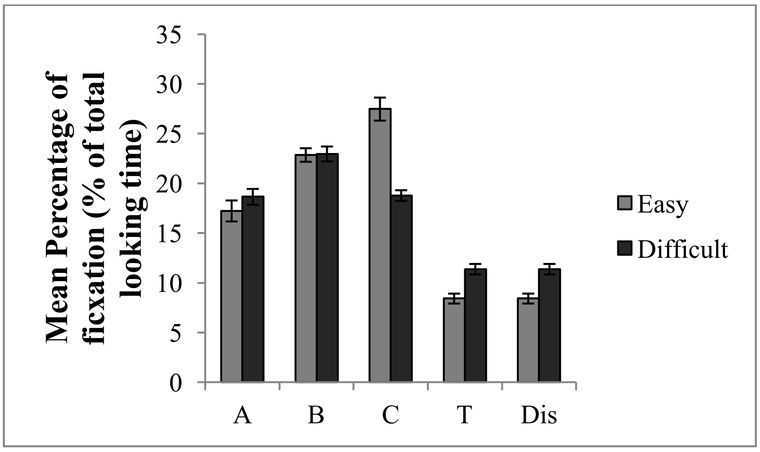


Figure 24: Mean percentage of fixation of each Type of Stimulus in easy and difficult trials (error bars represent SEM).

To test our assumptions about participants' greater interest in the distractor and the AB pair in Difficult than in Easy trials and of the preponderance of within- rather than between-domain saccades, we analyzed the saccades executed between the different pairs of pictures of the problem (Figure 25). We thus ran a two-way repeated-measure ANOVA with Transitions (AB, AC, BT, CT, CDis) and Condition (Easy, Difficult) as within subject factors. This revealed a significant interaction between Transition and Condition ($F(4,76)=4.5$; $p=.002$; $\eta^2_p=.192$). Planned comparisons revealed significantly higher mean rates of AB and CT saccades than AC and BT saccades ($F(1,19)=693.8$; $p<.001$; $\eta^2_p=.973$). It also revealed a significantly higher percentage of CDis saccades in the Difficult trials than in the Easy trials ($F(1,19)=32.2$; $p<.001$; $\eta^2_p=.629$) confirming more attention was allocated to distractors in the first than in the second, but no significant difference between the percentages of AB saccades in the two conditions. This last result, once again, can be due to these differences being only observable in the dynamics of the visual strategies.

Division of trials into slices

The mean time to solve Difficult trials was approximately three times longer than the mean time for solving Easy trials. Thus, participants might simply reiterate their procedure to solve the problem several times when the trials were more difficult, or, as we expected, differences in the repartition of key saccades and fixations (i.e. AB saccades, A and B fixations) could be different over time, in case of re-representation of the AB pair after the participants had observed the potential solutions. To test these hypotheses, we divided all trials in three equal slices (i.e., 1/3 of the total length of the trial), to observe differences in the dynamics of Easy and Difficult trials.

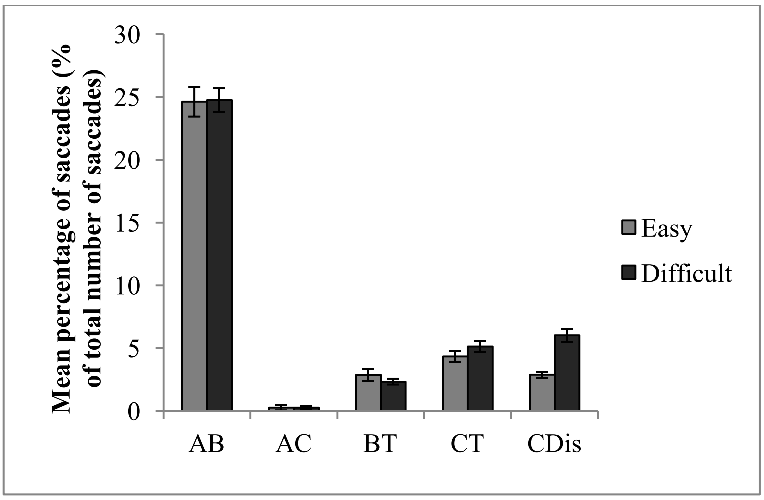


Figure 25: Mean percentage of saccades in easy and difficult trials (error bars represent SEM).

A three-way repeated measure ANOVA was used, with Type of Stimulus (A, B, T, Dis, U), Condition (Easy, Difficult) and Slice (first, middle, and last) as within-subject factors, was used to assess the evolution of fixations on the distractors and the source domain (Figure 26). It revealed a significant interaction between these three factors ($F(8,152)=25.3$; $p<.001$; $\eta^2_p=.571$). Planned comparison showed that the solution set (T, Dis, and U) was fixated longer in the first slice of the Difficult trials than in the first of Easy trials ($F(1,19)=71.5$; $p<.001$; $\eta^2_p=.790$), thus confirming that participants already looked at the solution set in the first third of the trials, which would trigger the re-fixation of A and B by participants, in our view. A was also fixated longer in the middle ($F(1,19)=40.6$; $p<.001$; $\eta^2_p=.681$), and the last slice ($F(1,19)=8.8$; $p=.008$; $\eta^2_p=.317$). B was not fixated longer in the Difficult than in the Easy trials in the middle slice ($F(1,19)=2.8$; $p=.109$; $\eta^2_p=.128$), but was in the last slice ($F(1,19)=7.1$; $p=.016$; $\eta^2_p=.272$). This confirms that the A and B pairs were of greater interest even at the end of Difficult trials, suggesting that participants tried to re-represent this pair.

To find further evidence of this re-representation of the AB pair, we also analyzed the AB, TDis, TU, and DisU saccades for differences across slices and conditions (Figure 27), using a three-way repeated-measure ANOVA with Transition (AB, TDis, TU, DisU), Slice (first, middle, last), and Condition (Easy, Difficult) as within-subject factors. There was a significant interaction between the Type of Saccade, Condition and Slice ($F(6,114)=15.1$; $p<.001$; $\eta^2_p=.443$). Planned comparisons confirmed a greater number of saccades between the solution set words in the first slice ($F(1,19)=60.1$; $p<.001$; $\eta^2_p=.760$), thus confirming that participants looked at the solution set as soon as the first slice in Difficult trials. The AB saccade was more frequent in the Difficult than in the Easy trials in the middle ($F(1,19)=11.4$; $p=.003$; $\eta^2_p=.375$) and the last slice ($F(1,19)=8.3$; $p=.010$; $\eta^2_p=.304$), which confirmed that the AB pair was of greater interest to participants in the middle and the end of Difficult trials more than in Easy trials. This suggests further, as the previous results obtained on fixation percentages of A and B, that participants tried to re-represent the relation between A and B after looking at the solution set.

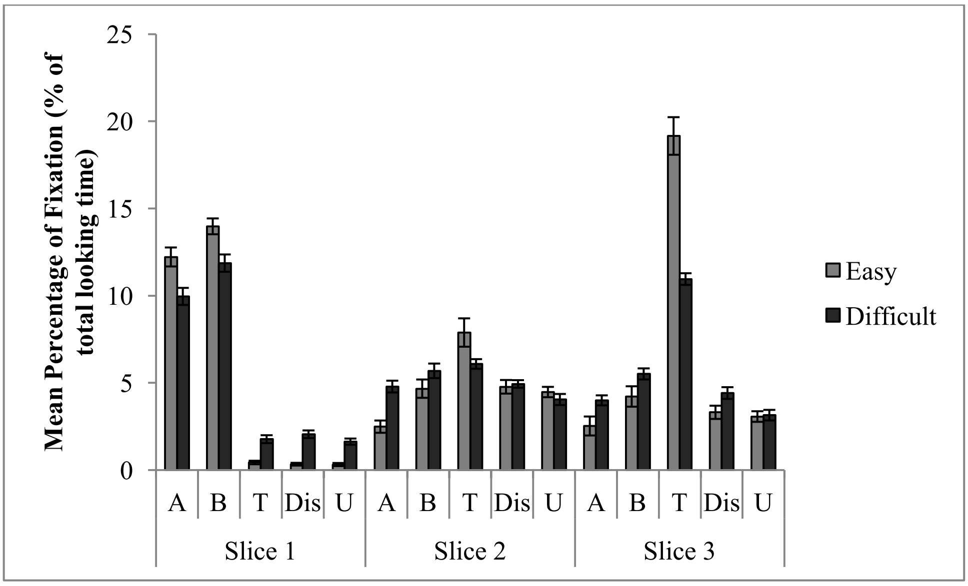


Figure 26: Mean percentage of fixation of each Type of Stimulus in first middle and last slice in easy and difficult trials (error bars represent SEM).

II. d. Discussion

Our hypotheses were that adults would have more difficulty to engage their inhibition against distractors in the case of difficult than of easy trials, because the relation between A and B which should constrain what kind of answer could be plausible would be harder to represent in a clear manner, and thus could not be used to constrain efficiently the response at

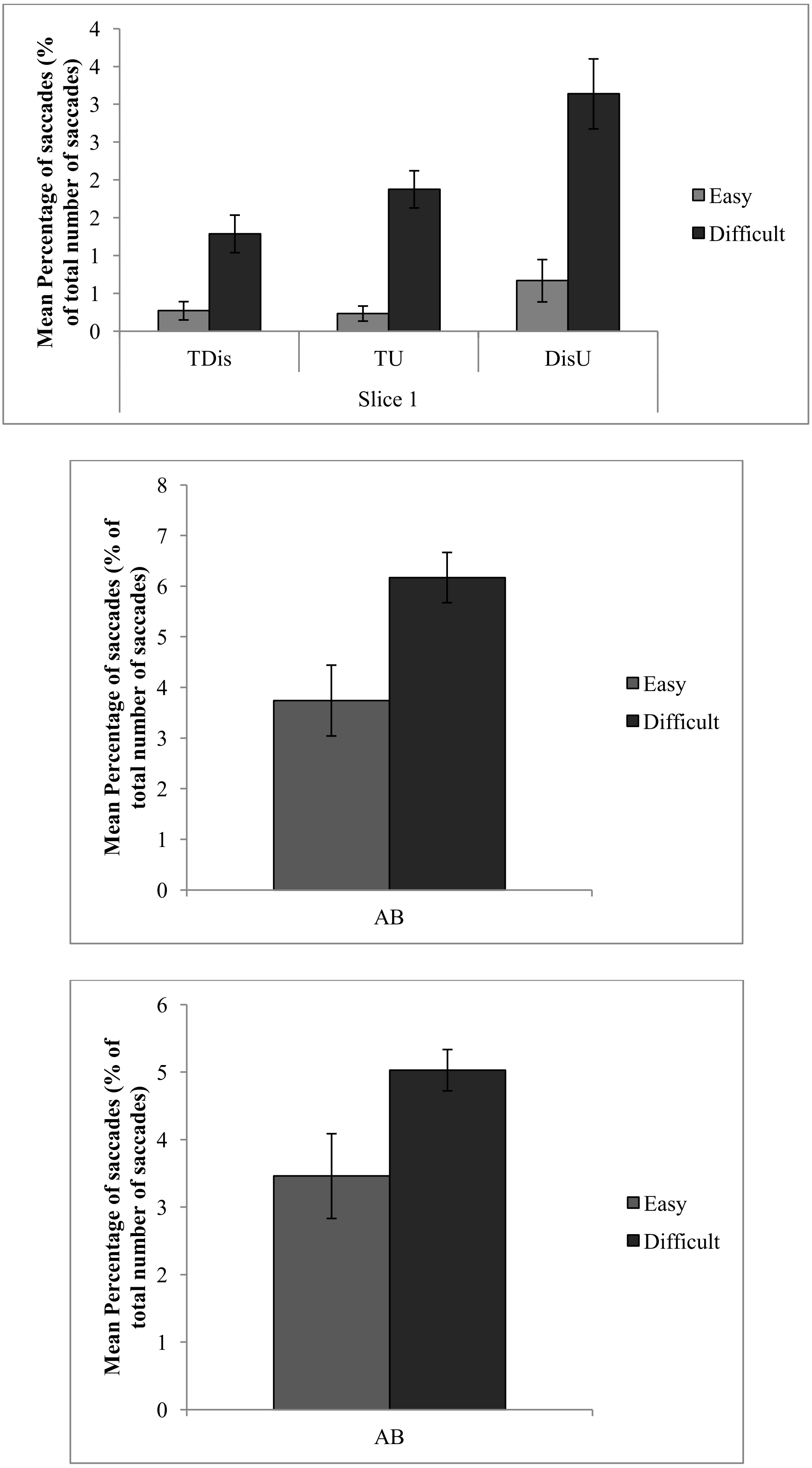


Figure 27: Mean percentage of each type of saccade in each slice in easy and difficult trials (error bars represent SEM).

first sight. Hence, participants should re-represent the source domain after seeing that the answer available could not be distinguished in their ability to fit the task's criterion for response. We also expected the same results as in the previous chapter in the A:B::C:? task to be found, i.e., more within- than between-domain saccades and a higher percentage of fixation on the C term of the problems, as would be predicted by the Path-Mapping Theory.

Indeed, we found the same results in the A:B::C:? task as those found in adults in the previous chapter, concerning the within- and between-domain saccades: AB and CT saccades were more important in participants' visual search of information than were AC and BT saccades. Once again, AB and CT saccades are most likely related to the inference of the relation between the pictures compared. However, the higher interest in C was not confirmed again. This might be due to difficult trials making participants have a more evenly distributed attention in terms of stimuli. Therefore, the previously observed higher attentional focus on C might be due to the simplicity of the trials used, which might have favored a type of strategy that resulted in longer fixations on C (i.e., a response construction as observed by Bethell-Fox et al., 1984). Indeed, the inference of what could be the solution (i.e., what is related to C in the same way as B is related to A) might have led to longer fixations on C, when a response-elimination strategy might lead to a more distributed attention.

One of the difficulties encountered by participants in difficult trials is the presence of distractors, as their increased looking rates on Dis and frequency of CDis saccades seem to suggest. This is the kind of results observed with children in the same task (see chapter II). This suggests that adults, even though they knew the constraints on the solution of analogical problems, considered this solution as a possibility or that it was difficult to discard distractors in difficult trials. A possible interpretation of the difficulty of the trials is that it is due to a lesser imageability of the relations between the words, hence the representation of this relation being less constraining on the solution as the category activated for the solution was larger. Indeed the semantic system seems to be differentially activated at different levels of imageability (Sabsevitz, Medler, Seidenberg, & Binder, 2005). Thus, it might be that at equal executive functioning, less imageable concepts are harder to manipulate than more concrete ones, causing higher interference from distractors. However, as this study did not manipulate this factor directly, further studies should investigate the role of imageability in analogical reasoning.

The time course of information gathering was also interesting, especially between the different types of trials. Participants seem to already evaluate the possible solutions in the first slice in difficult trials, and thus are less focused on the source pair of the analogy in this slice. Participants focus to the solution space during the first third of the trial in difficult trials is confirmed by their higher rate of fixation on T, Dis, and U in this slice, when compared to the first slice of easy trials. In the middle slice, participants made more saccades between A and B, which suggests that they made more returns on the source domain than in the easy trials, as was already observed by Bethell-Fox et al. (1984). This can be interpreted as participants trying to re-represent the relation between A and B after the test of their first hypothesis about this relation and the failure of finding a corresponding answer in the solution set. These results seem to indicate a difference between the search for the solution in the easy and difficult trials. In the difficult trials, participants do not simply reiterate the same strategy again and again, but adapt their strategy to their current knowledge of the problem. However, a response elimination is likely to have been used in difficult trials because there are some saccades in the solution set as soon as the first slice. Hypothesis testing and response elimination strategies are not consistent with Sternberg's (1977) description of encoding and inference as exhaustive processes. Indeed, when the difficulty to infer a relation increase, participants progressively refine their representation by looking at A and B again even after having looked at the alternatives. This suggests that these processes are not exhaustive, but have to be refined over time. Thus, the representation of C and the possible solutions play a role in the representation of the source pair, at least in difficult trials.

To conclude, the difficulty of these verbal trials seem to be a difficulty of representing the relation between A and B in a relevant manner for the task at hand, this resulting in a too lowly constrained representation of what would be the solution of the problems in the first attempt to solve them. This leads to the re-representation of the AB relation more narrowly with subsequent saccades between these pictures. However, the visual search is not a pure reiteration of the same strategy several times, but seems to adapt simultaneously to the representation participants make of the problem.

III. Experiment 2: Effect of an oppositely related-to-C distractor

III.a. Objectives and Hypotheses

The objective of this experiment was to test the effect of a related-to-C distractor which had a relation with C opposite to the relation B had with A (i.e., A and the distractor, and B and C, played the same role in the relation, but not A and C, and B and the distractor, as would be expected with a correct answer). This kind of distractors should lead to errors similar to the relational errors of children tested in the scene analogy task, even in adults, because of the A:B::C:? task's goal being focused on the similarity of the relations compared rather than on the roles played in these relations by the different elements constituting the problems. Indeed, errors implicating cross mappings (i.e., opposite-relation distractors) should remain unnoticed, because the relation is still similar even though the roles of the different object do not correspond, leading to a strong bias toward this kind of response, this bias being difficultly inhibited. Thus, we hypothesized that this type of distractor should lead to more errors in adults than simply related-to-C distractors (called other-relation distractors later) which do not share similarity in their relation to C with the relation between A and B. At the level of eye movements, we expected longer fixations on the opposite-relation than the simple other-relation distractors with which adults cope relatively easily. There should also be more CDis saccades, this saccade being linked to the encoding and inference of the relation between C and the distractor.

Results from Bethell-Fox et al. (1984) suggest that this augmentation of error could be due to a bypass of an evaluation of the response and of its comparison with other potential answers (i.e., a lower number of alternatives watched when the first alternative which is looked at is the correct solution) triggered by a high semantic similarity between the relations. Participants' reaction times should hence be faster: the answer looking appropriate, participants would not have to search for other responses. However, if the increase of wrong answers is due to a lack of inhibition of a prepotent answer, we would expect longer reaction times. Also, if the hypothesis about a lack of evaluation process is correct, there should be less saccades associated to evaluation of responses (TDis, TU, and DisU saccades) than in the other condition, when the inhibitory account would predict a higher rate of these saccades because of more comparisons between the two types of saccades.

We also manipulated another type of cognitive cost in this task: the order of presentation of the terms (i.e., A:B::C:? or ?:C::B:A, the latter being more demanding in terms of cognitive resources than the former; Barnes & Whitely, 1981). We thus made the hypothesis that the order of presentation of the words would make participants engage cognitive resources in the restructuration of the task. Cognitive resources being limited, they would have less resources to engage in the inhibition of distractors. Thus, we expected an interaction between the presentation of the task (left-to-right, or right-to-left) and the type of distractor, the opposite-relation distractors needing more resources than the simple other-relation distractors to be inhibited. This should cause scores being lower in the right-to-left with the former than with the latter distractors. In the right-to-left condition, at the level of eye-tracking data, we should also observe longer fixations on the distractors, and more saccades between C and Dis with the opposite-relation distractor than with the simple other-relation distractor.

Therefore, the experiment had a two within-subject factor design with Presentation (left-to-right, right-to-left) and Type of distractors (Related-to-C, Opposite-Relation) as factors. We recorded participants eye movements, responses and reaction times.

III.b. Methods

Participants

Participants were 27 adults (2 males, 25 females; M=19.3 years; SD=1.1; from 17 to 21). They were students at the University of Burgundy, participated willingly and were naive to the task. They were allocated randomly to one of the four versions of the task described below.

Materials

This verbal A:B::C:? task consisted in 22 trials: 2 training trials and 20 test trials. Half the trials (i.e. 1 training and 10 test trials) were presented with the direction of the A:B::C:? trials being from left to right (Left-to-Right condition), that is with A in the leftmost position, and the other half being presented with the A, B and C in the reverse order (i.e., with A in the rightmost position; Right-to-Left condition). Half the test trials in each of the above-mentioned conditions were presented with other-relation distractors that were semantically related to C (Semantic condition). The other half were trials with a distractor that were related to C with the opposite relation that the one used in the AB pair (Opposite condition). For example if A was "*cave*" and B "*bear*" (with the relation "lives in" linking them), and C was "*dog*", then the Target was "*flea*" and the distractor "*doghouse*", dogs being where fleas live and not where doghouses live. The distractors in the training trials were semantic distractors. Four versions of the task were designed following a Latin square: the trials being presented in the Left-to-Right with Related-to-C distractor condition in the first version were presented in the Left-to-Right with Inversely Related distractors condition in the second, in the Right-to-Left with Related-to-C distractor in the third, and in the Right-to-Left with Inversely Related distractors in the fourth. The same was done for the remaining three conditions of each version. The order of the trials was random.

Each trial was composed of 8 words written with a black ink on a white background and framed in a black rectangle (220x220 pixels). These pictures corresponded to the A, B, C, T, Dis and 3 U terms of the problem. The A, B, and C terms were displayed in a row at the top of the screen along with a fourth empty black square represented the location of the potential solution. The remaining pictures were presented in a row at the bottom of the screen.

The task was presented on a Tobii T120 eye-tracker (resolution: 1024x768) with the help of an E-prime (version 2.8.0.22) experiment embedded in a Tobii Studio (version 2.1.12) procedure for eye movements recording. Statistical analyses were ran with a Statistica 8 software.

Procedure

The procedure for testing participants in the A:B::C:? task was identical to the one used in chapter II Experiment 3.

III.c. Results

Behavioral data

To test our hypothesis about the link between inhibition engagement and goals of the task and the ability of changing increased the cognitive load of the task to interact with this engagement, we first ran a two-way repeated-measures ANOVA on Response Accuracies of participants with Type of distractor (Related-to-C, Inversely Related) and Presentation (Left-to-Right, Right-to-Left) as within-subject factors (Figure 28, left panel). Only the main effect of Distractor was significant ($F(1,26)=58.6$; $p<.001$; $\eta^2_p=.693$), but not the effect of Presentation ($F(1,26)=2.2$; $p=.148$; $\eta^2_p=.079$), nor the interaction between the two factors ($F(1,26)=1.1$; $p=.295$; $\eta^2_p=.042$). Planned comparison between the response accuracies in the trials with opposite-relation distractors in the Right-to-Left and Left-to-Right condition showed no significant difference ($F(1,26)=3.4$; $p<.075$; $\eta^2_p=.117$), thus invalidating our prediction of a higher distractor effect of opposite-relation distractors than simple other-relation distractors in the most costly of the two presentation conditions, and an influence of the global cognitive cost of the task on the inhibition of the distractor. Note that all errors were due to the selection of distractors, either opposite-relation or other-relation distractors depending on the condition.

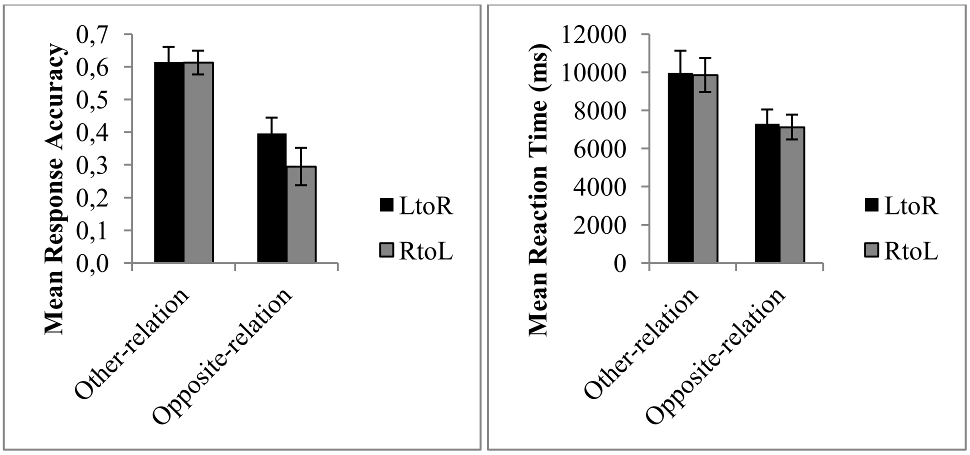


Figure 28: Mean Response Accuracy and Reaction Time in trials with Related-to-C and Inversely Related distractors in Left-to-Right and Right-to-Left presentation (error bars represent SEM).

The same analysis was run on participants' reaction times (Figure 28, right panel) to test the bypassing of the evaluation process, and the same significant main effect of Type of distractor ($F(1,26)=20.4$; $p<.001$; $\eta^2_p=.439$) was found, suggesting that some cognitive process was bypassed with opposite-relation distractors.

Eye movement data

A participant had to be discarded from further analyses because his/her data were not recorded at all. Apart from this subject, only 7 trials had more than 50% data missing, and were discarded from analyses.

To test our different predictions about higher rates of fixation on C than on other stimuli, and about percentages of fixation of Dis depending of the type of distractor and the type of presentation we also ran a three-way repeated-measure ANOVA with Type of Stimulus (A, B, C, T, Dis), Presentation (Left-to-Right, Right-to-Left) and Type of Distractor (Related-to-C, Inversely Related) as within-subject factors (Figure 29). It revealed a significant main effect of Type of Stimulus ($F(4,100)=31.2$; $p<.001$; $\eta^2_p=.555$), and a significant interaction between Type of Distractor and Type of Stimulus ($F(4,100)=15.0$; $p<.001$; $\eta^2_p=.376$), but not between the three factors ($F(4,100)=0.3$; $p=.856$; $\eta^2_p=.013$). Planned comparisons revealed that opposite-relation distractors were overall fixated more than other-relation distractors ($F(1,25)=18.8$; $p<.001$; $\eta^2_p=.429$), suggesting that less inhibition was engaged against these distractors than with simple other-relation distractors. There was no difference between the Right-to-Left and Left-to-Right Presentation conditions ($F(1,25)=.6$; $p=.461$; $\eta^2_p=.022$), which further invalidates our hypothesis about an influence of the cognitive cost of the task related to its presentation on the inhibition process. It also revealed that the mean percentage of fixation of C was greater than the mean fixation percentage of other stimuli ($F(1,25)=8;5$; $p=.007$; $\eta^2_p=.254$), even though it was not the greatest fixation percentage (i.e., B).

We also analyzed the percentages of saccades with a three-way repeated-measure ANOVA with Transition (AB, AC, BT, CT, CDis, TDis, TU, DisU), Type of Distractor (Related-to-C, Inversely Related), and Presentation (Left-to-Right, Right-to-Left) as within-subject factors (Figure 30), to assess the presence of predicted results about percentages of CDis saccades in the different distractor conditions, and especially in the more costly Right-to-Left presentation condition, as well as to test our hypothesis about evaluation between solution being bypassed with opposite-relation distractor. This analysis revealed a main effect of Transition ($F(7,175)=459.7$; $p<.001$; $\eta^2_p=.947$), a significant interaction between Type of Distractor and Transition ($F(7,175)=71.7$; $p<.001$; $\eta^2_p=.741$), and between the three factors ($F(7,175)=4.13$; $p<.001$; $\eta^2_p=.142$). Planned comparisons confirmed that the mean rate of AB and CT saccades was greater than the mean rate of AC and BT saccades ($F(1,25)=1377.5$;

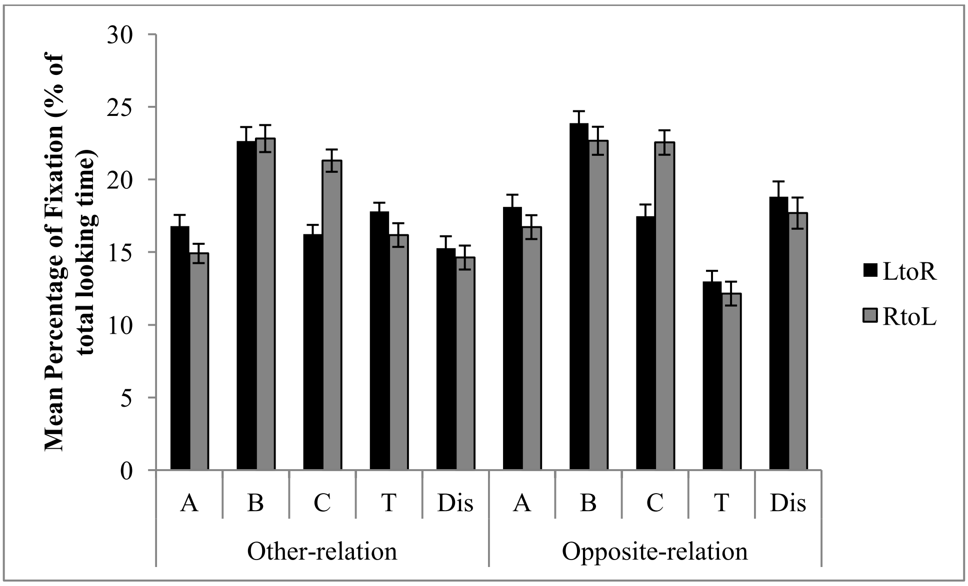


Figure 29: Mean Percentage of Fixation of each Type of Stimulus in trials with Related-to-C and Inversely Related distractors in Left-to-Right and Right-to-Left presentation (error bars represent SEM).

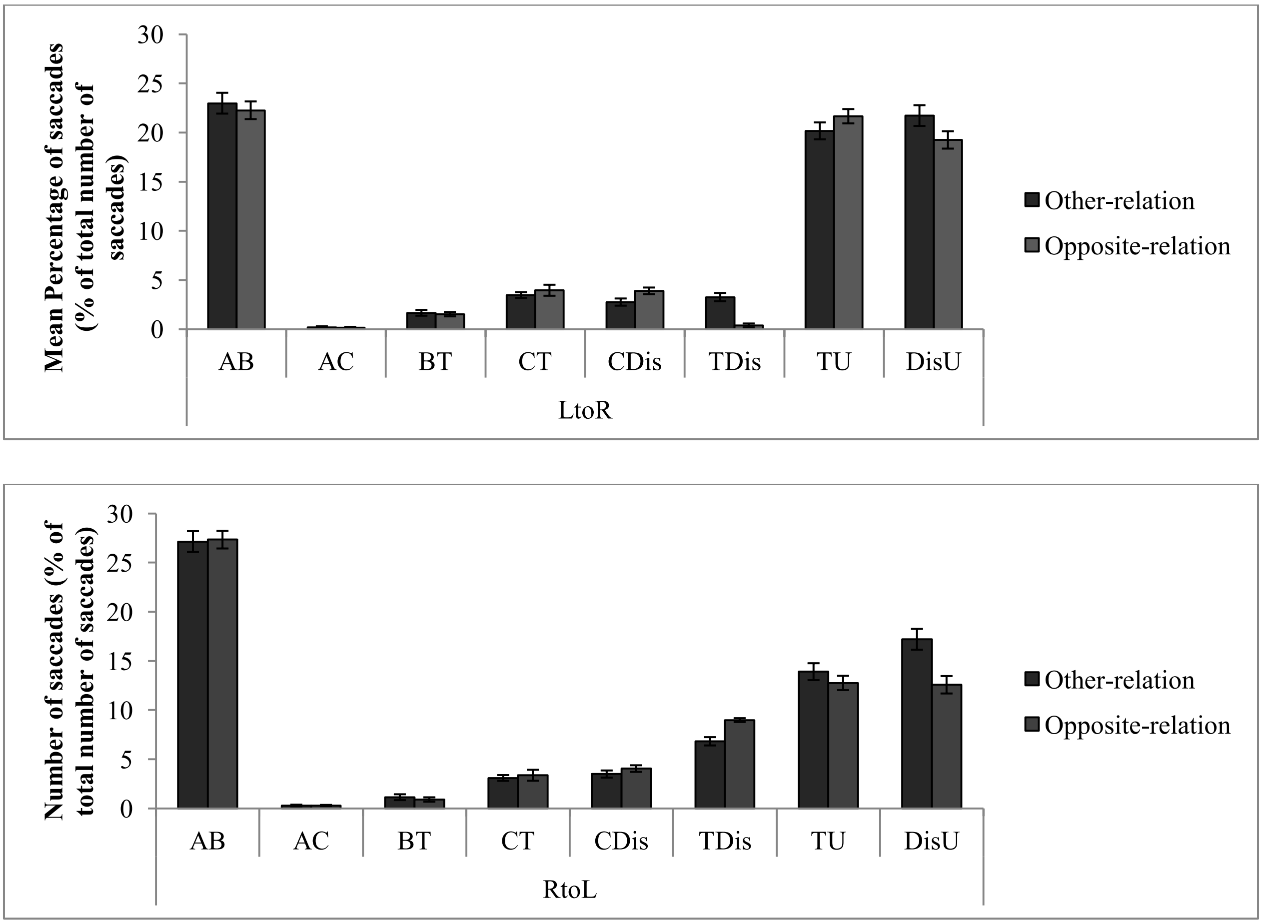


Figure 30: Mean Percentage of each type of saccade in trials with Related-to-C and Inversely Related distractors in Left-to-Right and Right-to-Left presentation (error bars represent SEM).

$p<.001$; $\eta^2_p=.982$), replicating previous findings about the preponderance of within-domain saccades in participants strategies in the A:B::C:? task. However, there was neither a significantly greater percentage of CDis saccades when the opposite-relation distractor was present than when the other-relation distractor was present ($F(1,25)=1.4$; $p=.256$; $\eta^2_p=.053$) nor a significant difference between the percentages of CDis saccades between types of distractors in the right to left presentation of the problems ($F(1,25)=1.0$; $p=.339$; $\eta^2_p=.037$), which infirmed our hypothesis about inhibition engagement differences between these two conditions. There was also significantly less saccades between solution options (TDis, TU, and DisU saccades) in the problems with opposite-relation distractors than with other-relation distractors ($F(1,25)=46.6$; $p<.001$; $\eta^2_p=.651$), which suggests that the process responsible for the evaluation of the solution and its comparison to other potential solution is bypassed with the opposite-relation distractor.

III.d. Discussion

The present experiment tested our hypotheses about opposite-relation distractors making participants engage less inhibition against them than simple other-relation distractors, because of their link to the main goal of the task, and the modulation of this engagement of inhibition by cognitive costs due to the restructuration of the problems presented. We also hypothesized that participants would tend to make less comparisons between the different solution options suggesting a bypass of the evaluation process, due to the apparent relevance of the relation between the opposite-relation distractor and C to the task (i.e., its semantic similarity with the relation between A and B). The higher distractor effect of opposite-relation distractors due to the semantic similarity of the relation they elicited with the relevant relation was confirmed by lower response accuracy and longer fixations on these stimuli in this condition than with usual other-relation distractors. Indeed, opposite-relation distractors were chosen in nearly 60% of the trials. However, the frequencies of CDis saccades did not differ with on type of distractor of the other. This might be explained by the fact that distractor were easy to inhibit in the case of other-relation distractors, and that the relation was evident and that participants did not try to inhibit the distractor in the case of opposite-relation distractors, both provoking a low rate of CDis saccades. Our hypothesis about the interaction of the costs of the presentation of the task with the inhibition of the distractor was invalidated. There was no differences between the left-to-right and right-to-left presentations of the task either in the response accuracy of the participants, or in the fixation and saccades associated with the distractors. There was evidence that the evaluation process was bypassed: reaction times, and percentage of saccades associated with the comparison of the different answers were lower with the opposite-relation distractors than with the other-relation distractors.

Behavioral as well as eye movement observations suggest that the two types of distractors studied in this experiment differ in their impact on analogical reasoning: lower performance, lower reaction times, longer rates of fixation on Dis and a decrease in the number of solution comparisons were observed in the case of opposite-relation distractors when compared to the condition involving distractors related to C by any relation. This difference of effect might be due to high semantic similarity between the relations between, on one hand, A and B, and, on the other, C and the opposite-relation distractor. This semantic similarity is the constraint stressed by the task for achieving its main goal, i.e., finding something that has a similar relation to C as B has to A, however it does not take into account the constraint (emphasized here by the instructions given by the experimenter) to also control for the role equivalences of the elements in the relations. Thus, choosing the opposite-relation distractor is equivalent to a cross-mapping in terms of role confusion, even though it is not due to perceptual similarity (Gentner & Toupin, 1985). We argue that the strength of these distractors is due to their presence evoking a relation that is highly similar to the one searched for by participants, thus being very salient because of its link to the main goal of the task. We also argue that its efficiency to make people give the wrong answer is due to this similarity. Hence, participants overlook the process of evaluating the mapping resulting from the selection of this solution. Indeed, participants had lower reaction times and made lower rates of saccades inside the solution set to compare answers in this condition than in the other, simpler condition, which suggests such process bypassing. Thus, it seems likely that the opposite-relation distractors were not seen as errors due to the semantic similarity between their relation to C and the relation between A and B, thus preventing participants to engage inhibition against this type of answer.

Hence it seems that the A:B::C:? task, due to its focus on the relational similarity instead of emphasizing the similarity between roles of the different elements in the two domains compared, implicitly relaxes the constraint participants should put on the matching roles between elements of the two domains. This is coherent with previous experiments by Spellman & Holyoak (1996) showing that the goals the participants were given influenced their analogical reasoning, and with the theoretical accounts of Holyoak & Thagard (1989) which models the effect of such pragmatic constraints on mapping, and of Salvucci & Anderson (2001) which integrate mapping into pragmatic constraint of problem solving tasks in the ACT-R architecture, thus making action rules be triggered as soon as the conditions to trigger them are met. In this latter model, the present results would be easily modeled using a similarity criterion between the relations triggering the model's answering. The LISA model uses inhibition as a basic feature of its processes. However, it does not define any a priori relation between inhibition and goals of the task, even though goals might influence inhibition engagement by affecting the frequency of activation of relations relevant for the goals in working memory, thus leading to differential patterns of inhibition between elements of the domains compared.

We also expected an interaction between the type of distractor and the direction of the presentation of the problems (i.e., from left to right or the reverse) because of the limitation of cognitive resources. Indeed, if a right-to-left presentation is more costly in terms of these resources (Barnes & Whitely, 1981), other cognitively demanding processes like engaging inhibition against irrelevant information should be less efficient. We did not find any result coherent with this view. The response accuracy of participants and the percentages of fixations of Dis and of saccades involving this distractor were the same in the right-to-left presentation condition when there was a higher cost of finding a distractor irrelevant (i.e., opposite-distractor relation) than when it was less costly (i.e., other-relation distractors).

IV. General discussion

Whenever the main characteristics of the visual strategies used in A:B::C:? problems by adults remain stable (i.e., more within- than between domain saccades, focus on C), difference arose between the different conditions of these two studies. When the inference of the relation between A and B is more difficult, they seem to re-encode several times this relation, after trying to eliminate some solutions from the solution set. This could be linked to the imageability of the relational concept linking the two pairs in the problem: less imageable relations could lead to a difficulty to activate a proper role category for the solution of the problem, analogical reasoning tasks having been shown to automatically activate category representations of the elements in the domains compared (Green, Fugelsang, Kraemer, & Dunbar, 2008; Green, Fugelsang, & Dunbar, 2006), which would explain the use by participants of a response elimination strategy even without an overload of working memory, as was observed by Bethell-Fox et al. (1984). Thus a difficulty to interpret the relation increased the number of controls of the results of the analogical reasoning processes, as can be seen in the increase in reaction time in the difficult condition in comparison to the easy one in Experiment I. However, some manipulations might bypass the evaluation process of the products of analogical reasoning, as the second experiment seems to suggest. This bypassing of the evaluation process seems to be triggered by the similarity conveyed between the relations by opposite-relation distractors and C on one hand, and between A and B on the other. Indeed the main goal of the task being to find the object that has the same relation to C as B has to A, the similarity of the relation activated by this lure might trigger answering before any evaluation process has been run, because of the obviousness of this similarity. This bypassing of evaluation processes is further suggested by faster reaction times in the condition with opposite-relation distractors in comparison to the condition with simple other-relation distractors. This type of error can be related to the same goal neglect of children performing the scene analogy task, even though this task specifically focus on this aspect (see chapter II).

Thus, the inherent goal of the A:B::C:? task (see chapter II) might accentuate certain constraints on the similarity of relations leading participants to longer processing of the problem (Experiment I) or, to the contrary, to overlook certain constraints on the solution, like the mapping between the different elements of the two domains constituting the problem. This shows, like the results presented in chapter II, how the goals emphasized by the task influence the way people apprehend its solution, which is coherent with theoretical accounts of analogical reasoning focusing on pragmatics (Holyoak & Thagard, 1989; Salvucci & Anderson, 2001). However models of mapping have difficulties integrating problems linked to the inference of relations, because of the preconstruction by experimenter of the relational structures and, in certain cases, their similarity ratings.

A new method for classifying scanpath

Chapter IV: A new method for classifying scanpath[1]

I. Background

Humans rely heavily on vision for virtually every task they do (e.g. categorization, spatial orientation, problem solving, etc.) and it remains a privileged way of acquiring information about the environment. In the case of problem solving, what information is sought and how this search is organized through time to come to a solution for the problem (i.e. visual strategies) may help researchers understand which solving strategies are used. Attention and gaze-fixation are highly correlated, especially for complex stimuli (Deubel & Schneider, 1996; He & Kowler, 1992) and the fixation time for a given object is correlated with its informativeness in a scene (Nodine, Carmody, & Kundel, 1978). This argues in favor of studying eye-movements as indicators of the application of a specific strategy through control of attention.

Eye-tracking data, especially if they involve scanpaths — i.e., the complete visual trajectory of a participant's eye movements during the task — are often complex and hard to analyze. For this reason scanpath information is often reduced to static information about the participant's gaze times at specified locations. This simplification, while certainly easier to analyze, generally fails to fully capture the temporal aspects of the data involved in visual strategies. Even when an attempt is made to take into account temporal aspects of the data, it is often difficult to compare two scanpaths because, in general, they differ in length and complexity. Jarodzka et al. (2010) have developed a method that is able to compare any two scanpaths. As the Jarodzka et al. algorithm plays a key role in the analysis that follows, we will describe our variant of this algorithm in some detail below. We combined this scanpath-comparison algorithm with multidimensional scaling and a neural-network classifier to demonstrate that children's analogy-making strategies, as reflected in their visual search patterns across three different problems, are measurably different from those of adults.

[1] This chapter was published as Glady, Y., Thibaut, J. P., & French, R. M. Visual Strategies in Analogical Reasoning Development: A New Method for Classifying Scanpaths. *Proceedings of the 35th Annual Meeting of the Cognitive Science Society* (pp. 2398-2403).

We are not the first to use eye-tracking technology to study analogy making, but this type of analysis is, nonetheless, still in its infancy. Eye-tracking techniques were first used by Bethell-Fox, Lohman, & Snow (1984) to study strategies when reasoning by analogy. They found strategic differences in adults with high or low fluid intelligence when solving geometric A:B::C:? problems. More recently, Gordon & Moser (2007) investigated adults' strategies in scene analogy problems. Thibaut, French, Missault, Gérard, & Glady (2011) also used an eye-tracker to examine infants' gaze locations and item-to-item saccades during an analogy task. However, all of these studies focused on what information was searched for by participants as they attempted to solve the analogy problem.

None of this research compared participants' global scanpaths. In other words, previous eye-tracking studies have focused on local aspects of participants' scanpaths as a means of revealing part of the dynamics of visual search in doing analogy problems. By contrast, in the present study we will use participants' global scanpaths in our attempt to respond to the question of whether children have different visual search strategies than adults when solving visual analogy problems. Woods et al. (2013) showed that the organization of search in visual-attention tasks becomes less variable over the course of development. Because the tasks we used rely on visual attention, we expected children to have more variable scanpaths than adults.

II. Methods

II. a. Participants

Subjects were 20 adults (14 females, 6 males; mean age=20;5 years; SD=2.21; range: 17 to 27), students at the University of Burgundy and naïve to analogical reasoning tasks and 26 6-year-olds (16 females, 10 males; mean age= 79.5 months; SD=3.6; range: 73 to 84). For children participating in this experiment, parents' informed consent was required from their parents.

II. b. Materials

Three tasks, each composed of three training trials and four experimental trials, constituted the experiment (see Figure 31). The first task was a scene analogy problem task, the second a standard A:B::C:? task and the third an A:B::C:? task with the items composing the problems put within a context. Each problem of each task was composed of 7 black and white line drawings.

In the scene analogy problems, the top scene was composed of two elements depicting a binary semantic relation (e.g. a cat chasing a mouse). One of these two elements had an arrow pointing to it. The bottom scene was composed of five drawings: the two elements depicting the same relation as in the top picture (e.g. a boy chasing a girl), a distractor item, and two elements that were consistent with the scene but that had no salient relation with the elements of the relation. These pictures (501x376 pxs) were based on Richland et al., (2006) except for the distractor that was chosen not to be perceptually, only semantically, related to one member of the relation in the bottom picture.

In the standard A:B::C:? trials, the A, B, C drawings were presented in the top row along with a black empty square symbolizing the location of the solution. The four remaining pictures (the Target, a Related-to-C Distractor, and two Unrelated Distractors) were presented in a row at the bottom of the screen. The size of each picture was 200x195 pxs. The A:B::C:? task within context was constituted of two scenes (501x376 pxs). The top picture was composed of two black and white line drawings with a relation between them (e.g. a wolf and meat, with the wolf looking at the meat) with a contextual cue (e.g. a horizontal line for the horizon or the lines of the joining walls and floor for a room). The bottom picture was composed of the five remaining drawings: the C term, the Target, the Related-to-C Distractor and the two Unrelated Distractors. This task differed from the first task in that it was the C term that was pointed at with an arrow, and not one of the elements constituting the source relation. It differed from the second task because of the different pictures constituting the problems being grouped in two scenes, but equivalent to the standard A:B::C:? task in other respects.

The materials of the last two tasks were based on materials previously used by Thibaut et al. (2011). The four trials of each task were two trials with weak association strengths between A and B, C and T, and C and Dis, and two with strong association strengths in order to equilibrate this factor.

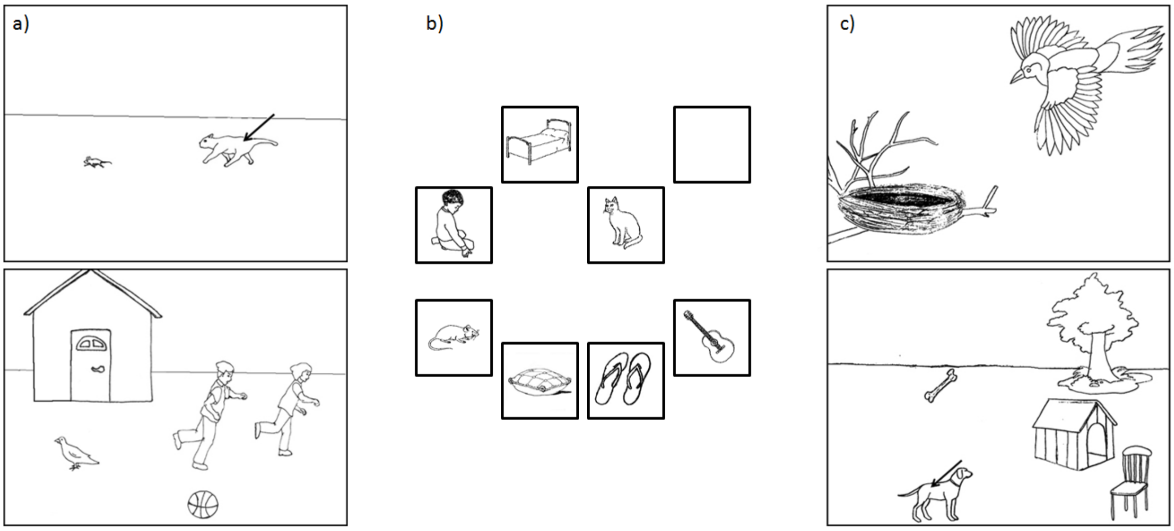


Figure 31: Presentation of the three tasks used for this experiment: a) scene analogy task, b) standard A:B::C:? task, c) scene-oriented A:B::C:? task

The tasks were displayed on a Tobii T120 eye-tracker device with a 1024x768 screen resolution.

II. c. Procedure

Appropriate controls were carried out to ensure that the participants knew what the items in each of the problems were and that they understood the instructions. In the first task, they were asked to point to the element in the bottom scene that played the same role as the one which had an arrow pointing to it in the top scene. The two others tasks were administered as in Thibaut et al. (2011). Eye-tracking data was gathered from moment of the initial presentation of the problem to the moment a choice of one of the answers was made. The participant's scanpath for a particular problem consisted of a record of his/her gaze-fixation points taken every 8ms.

II. d. Data Analysis

The goal of this analysis is to compare the sets of children's and adults' scanpaths and to show that there are quantifiable differences in the two. To do this we use a combination of (a variant of) Jarodzka et al.'s (2010) scanpath-comparison algorithm, multidimensional scaling and a neural-net classifier. As the latter two techniques are well known, we will not discuss them at length. However, the Jarodzka et al. algorithm is relatively recent and requires explanation.

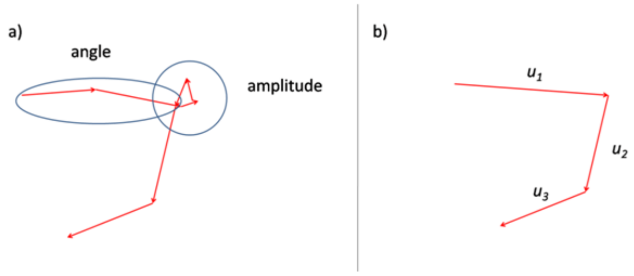


Figure 32: Simplification of a scanpath

Jarodzka et al. (2010) scanpath-comparison algorithm

The algorithm is designed to determine the similarity of any two scanpaths. It consists of two phases, a simplification phase and a comparison phase. A scanpath is considered to be made up of a series of "saccade vectors," i.e., a connected series of vectors whose endpoints correspond to coordinates of successive gaze points (Figure 32a). First, the scanpath is simplified by combining into a single vector two consecutive saccade vectors if:

i) their combined length does not exceed 200 pixels in amplitude (i.e., each is very small) and

ii) they are nearly in straight line (i.e., the angle between them is between 2.62 and 3.67rad).

In other words if a saccade vector is very small or very linear with respect to its predecessor in the scanpath, the two vectors are combined (Figure 32b).

Once each of the two scanpaths has been simplified, they can be compared. We begin by giving an intuitive explanation of how this is done. Assume, for example, there are two simplified scanpaths, S_1 and S_2 made up of 3 and saccade vectors, respectively. In other words, $S_1 = \{u_1, u_2, u_3\}$ and $S_2 = \{v_1, v_2, v_3, v_4\}$. Note that these saccade vectors are ordered in time. For example, in S_1, the saccade vector u_1 is followed by u_2, which is followed by u_3. To compare S_1 and S_2, we need two scanpaths of the same length. To achieve this, we will "stretch" each scanpath by adding immediate repetitions of saccade vectors, so that they both have the same length. Our goal is to find the two stretched scanpaths, SS_1 and SS_2 that are as similar as possible with respect to the chosen metric (orientation, length, etc.). This similarity will be the measure of the distance between S_1 and S_2.

a)

	v_1	v_2	v_3	v_4
u_1	$\Delta(u_1, v_1)$	$\Delta(u_1, v_2)$	$\Delta(u_1, v_3)$	$\Delta(u_1, v_4)$
u_2	$\Delta(u_2, v_1)$	$\Delta(u_2, v_2)$	$\Delta(u_2, v_3)$	$\Delta(u_2, v_4)$
u_3	$\Delta(u_3, v_1)$	$\Delta(u_3, v_2)$	$\Delta(u_3, v_3)$	$\Delta(u_3, v_4)$

b)

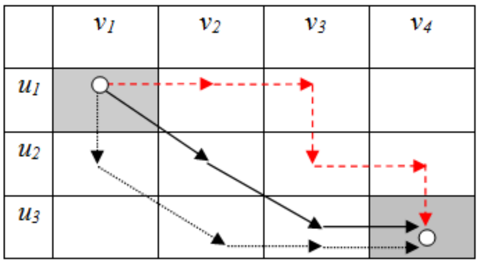


Figure 33: Saccade-vector difference table (a): Each of the saccade vectors from each of the two scanpaths are compared based on the chosen metric. (b) The comparison of each pair of stretched scanpaths corresponds to a traverse of the table from the upper-left to the lower-right corner of the saccade-vector difference matrix (the only directions of movement permitted are down, right and diagonally down-and-right). We find the path that produces the lowest total difference value and this value is the similarity measure assigned to S_1 and S_2

The easiest way to illustrate this stretching is by means of a saccade-vector difference table for the two scanpaths, S_1 and S_2, defined above.

A saccade-vector difference matrix is first created (Figure 33a). Each of the saccade-vectors making up one of the scanpaths S_1 is compared to each of the saccade-vectors of the other scanpath S_2, according to a metric, generally, vector magnitude or orientation (length in our study). Once this table is constructed, we consider all paths through the table that begin with the comparison of the first saccade vectors in both scanpaths (i.e., cell (1, 1) of the table, $\Delta(u_1, v_1)$) and end with a comparison of the final saccade vectors in each scanpath (i.e., cell (3, 4) of the table, $\Delta(u_3, v_4)$) and always move to the right, down, or diagonally down-and-right. Three examples of paths through the matrix are illustrated in Figure 33b. Each path through the table corresponds to the comparison of two specific stretched scanpaths. For example, the uppermost path shown corresponds to a comparison between $SS_1 = \{u_1, u_1, u_1, u_2, u_2, u_3\}$ and $SS_2 = \{v_1, v_2, v_3, v_3, v_4, v_4\}$. This path corresponds to the sum of the values in the cells (1,1), (1,2), (1,3), (2,3), (2,4), (3,4) of the saccade-vector difference matrix. When all of these paths through the matrix are considered, the path which has the smallest value (i.e. the smallest cumulative sum of comparisons) is selected. This path corresponds to the two stretched scanpaths that are the most similar. This value, normalized by the number of comparisons done, is the similarity measure assigned to the comparison of scanpaths S_1 and S_2.

Note that the algorithm as described here differs from Jarodzka et al. (2010) in that it does not rely on the more complex Dijkstra (1959) tree-search algorithm. Instead, we constructed a matrix, cell by cell, with the lowest cumulative sum of comparisons possible for each cell while taking into account the constraints put on the comparisons of the two scanpaths (navigate rightward, downward, or diagonally downward and to the right). In our example, the final distance value between S_1 and S_2 is the cumulative sum in C(3,4) normalized by the number of steps taken through the matrix. This algorithm was computationally less complex for identical results.

The Jarodzka et al. (2010)/MDS/MLP algorithm applied to scanpaths of analogy problems

We only compared the scanpaths from strictly identical problems, but not different trials from the same task. Thus, when we were comparing an adult scanpath and a child's scanpath, the disposition of the items in the problem they were solving was identical.

In this way, for a given set of isomorphic problems (i.e., where all of the items were in identical places on the screen), we computed the differences between all pairs of scanpaths. In other words, if there were S_1 to S_n scanpaths from children and A_1 to A_m scanpaths from adults on the same set of isomorphic problems, we computed the similarity of all pairwise comparisons of scanpaths S_i versus S_j, S_i versus A_j, and A_i versus A_j for all i and j.

Once we had calculated the mean differences between scanpaths generated by each participant in each task, we used Multidimensional Scaling to obtain the coordinates on a 2D map that best preserved the distance between scanpaths. As can be seen in Figure 34, for each of the three tasks, the scanpaths clustered according to participant type (Adult or Children). We verified this clustering using a 3-layered perceptron (MLP) with a bias node on the input and hidden layers (5 hidden units, learning rate = 0.05, momentum = 0.9) with the coordinates of each scanpath on the MDS map translated into bipolar values and concatenated on input. We used a Leave-One-Out cross-validation technique to test the robustness of the classification. Leave-One-Out cross-validation is a standard technique in machine learning whereby the classifier (in this case a neural network) is trained on all items but one. Once training is complete, the classifier is tested on the item that had been left out to see whether or not it is classified correctly.

III. Results

Using the method of analysis described above, we did a pairwise comparison of all scanpaths generated by adults and children on isomorphic analogy problems. We then conducted a multi-dimensional scaling analysis of this data, which produced the location-map clusters shown in Figure 34. These points are a 2D representation that best reflects the distances between the scanpaths. The crosses correspond to children's scanpaths; the circles correspond to adults' scanpaths.

The Jarodzka et al. (2010) method along with Multidimensional Scaling led to a 2D location map that best represented the relative distances between the set of scanpaths, as calculated by the Jarodzka et al. algorithm (Figure 34). A three-layered feedforward backpropagation network (MLP) with a Leave-One-Out cross-validation method, was used to test the robustness of a classification of the points representing the two groups (i.e. children and adults). For the scene analogy and A:B::C:? tasks (Figure 31a and b), the network classified 74% of the participants correctly based on their scanpath (70% of the 20 adults and 78% of the 23 children for both tasks). For the real-world A:B::C:? task, the network classified 72% of the subjects correctly (65% of the adults and 78% of the children). This was

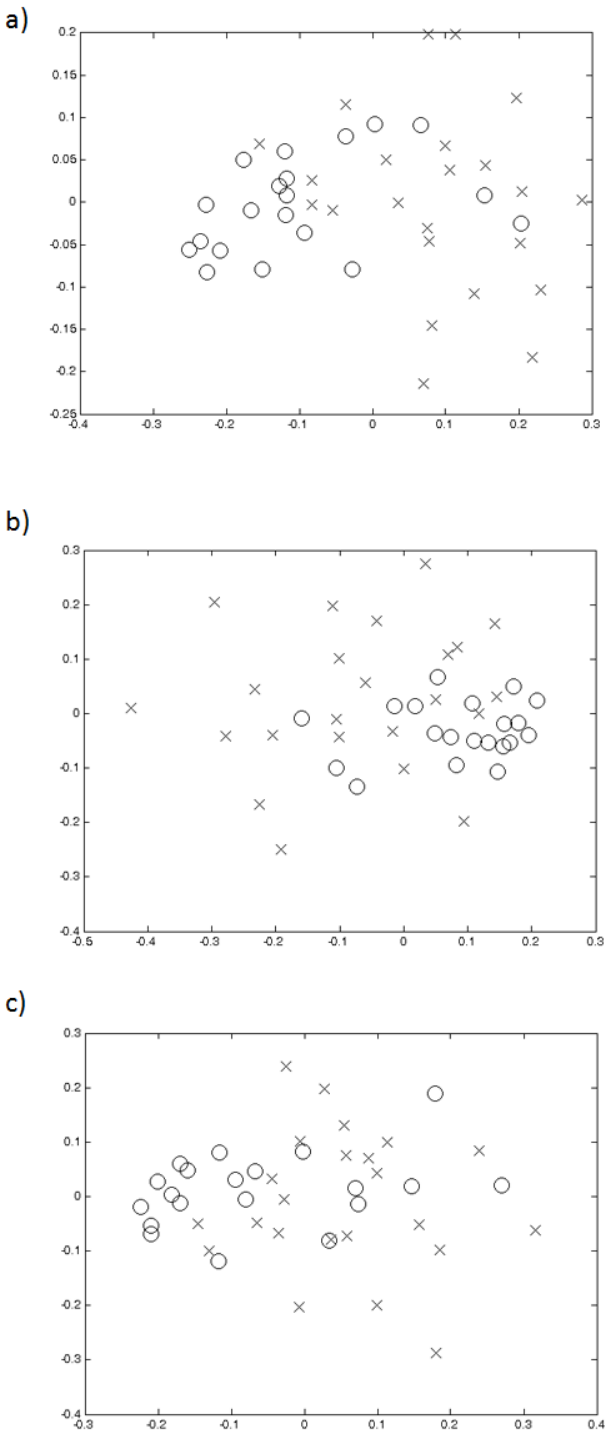


Figure 34: Location-map of an MDS analysis of the relative differences among participants for the scene analogy task (a), the standard A:B::C:? task (b), and the scene-oriented A:B::C:? task (c).

significantly above chance (50%) for each task (binomial test: $Z=14.89$; $p<.001$ for the first and second; $Z=14.30$; $p<.001$ for the third). Intuitively, this result can be seen in Figure 34. The adult group tends to be more homogenous than the children as the crosses (children's scanpaths) are more scattered than the circles (adults' scanpaths), and this is reflected in the high degree of accurate classification of the MLP.

IV. General discussion

The present study addressed the following question in a novel manner: Do children and adults have different visual strategies in analogical reasoning tasks? To answer this, we used an eye-tracking methodology whose data were analyzed by a combination of the Jarodzka et al. (2010) scanpath-comparison algorithm, the transformation of this data into a 2D location map using multidimensional scaling, and, finally, a quantitative adult/child classification by means of a feedforward backpropagation network. The neural-net classification was done by training the network on the scanpath data for all but one participant. Once the network was trained, it was tested on the one scanpath that was left out of the training set. This was done for each participant's scanpath data and the result was scored according to whether the network classified the test scanpath correctly or not. The results obtained with this method agree with previous results from Thibaut et al. 2011 who also showed, by analyzing item gaze times and the number of saccades between items that adults and children differed in their search strategies in the standard A:B::C:? analogy task. The present work, using an approach based on individuals' entire scanpaths, also extends this previous work to scene analogy problems and scene-oriented A:B::C:? problems. This scanpath analysis showed, among other things, that children's scanpaths were more variable than those of adults in the three tasks. These differences support the hypothesis of the key role of executive functions in analogy making because the lower variability of adults' scanpaths is indicative of them applying, through control of attention, a previously adopted plan for solving analogy problems (Woods et al., 2013)

The scanpath analysis presented in this paper provides a means of studying various search strategies in analogy making. The technique presented in this paper overcomes thorny problem of comparison of scanpaths of different lengths and allows to take into account the dynamic features of search, which are largely missed in other, more static eye-tracking approaches based on item fixation times. It could also be used, for example, to confirm differences in analogy-making strategies observed in adults in Bethell-Fox et al. (1984) and to classify participants based on their scanpath data (i.e., “elimination strategies” for participants with low fluid intelligence and “constructive matching strategies” for participants with high fluid intelligence). This method is, of course, not limited to studies of analogy-making, and could be used with any other type of problems whose crucial information for its solution could be presented on a screen.

To conclude, the method of scanpath analysis presented in this paper provides a new tool to analyze the dynamic aspects of search strategies in a wide variety of experimental contexts. As shown by the results, this method is sensitive to global differences between scanpaths and is useful to discriminate clusters of strategies. In this paper it has been used to show that children’s and adults’ differ in their variability while solving analogical reasoning problems, suggesting the involvement of executive functions in such tasks. However, to fully understand the causes of these differences, it is inevitable to use local information. Thus, it should be used in combination of other existing methods, in particular, Area-of-Interest methods that provide information on *what* information is sought and how long it is watched (informativeness of stimuli), since this information is not captured by the Jarodzka et al. method. On the other hand, Area-of-Interest methods give limited information about the dynamic progression of search, something which is captured when full scanpath information is used. In short, the Jarodzka et al. (2010), combined with an MDS analysis and a classifier (backpropagation networks, Support Vector Machines, etc.), provides a potentially far-reaching tool for analyzing participants’ dynamic strategies in various problem-solving contexts.

Cognitive flexibility involvement in children's analogical reasoning

Chapter V: Cognitive flexibility involvement in children's analogical reasoning[2]

I. Background

In the present experiments, we show that a preliminary interpretation of an AB relation influences the way a subsequent A:B::C:? problem will be solved. We discuss these results in terms of inhibition and flexibility, two executive function components potentially involved in analogical reasoning which thus might be implicated in the solution of A:B::C:? problems (see Richland et al., 2006; Thibaut et al., 2010a, 2010b).

Consider a simple A:B::C:? analogy: *bird:nest::dog:?*. To find the solution among a set of possibilities, one has to encode the terms of the analogy, to analyze both sides of the problem (i.e., A and B on one side; C and the solution set on the other), thereby constituting a set of potential relations unifying the two pairs compared. This will give an interpretation of the AB pair that is a semantic relation connecting *bird* with *nest*. One might also align *bird* with *dog* (Markman & Gentner, 1993), while keeping in mind that the relation between *bird* and *nest* should also hold between *dog* and the solution item. While searching for an interpretation of the pairs, especially when no relation comes immediately to mind, or when no common unifying relation immediately pops out, working memory is needed to keep the representations of the pairs active in order to compare them. In many cases it is also necessary to inhibit salient relations that make no sense in the context of the analogy at hand and/or to be flexible when new relations must be found (Morrison et al., 2004; Richland et al., 2006; Thibaut, French, Vezneva, et al., 2011; Thibaut et al., 2010b; Waltz et al., 2000). For example, if a relevant relation is found for AB (e.g. "the bird *sleeps/lives* in the nest", with the solution being "*doghouse*"), one can look for an item that will satisfy the same "*sleeps/lives in*" relation, such as *doghouse*, based on the mapping of *bird* to *dog* and the equivalence of relations in the source and the target, to complete the second pair.

[2] Parts of this chapter were published as Glady, Y., Thibaut, J. P., French, R. M., & Blaye, A. Explaining children's failure in analogy making tasks: A problem of focus of attention?. *Proceedings of the 34th Annual Meeting of the Cognitive Science Meeting*. and submitted as a journal article.

The comparison between the two domains can also involve re-representation (Gentner, 1983). Representations of the source and target domains and their mapping can change over time to increase the consistency of the overall correspondence of the two domains. To illustrate how cognitive flexibility (i.e. the ability to shift from one representation of a stimulus to another) might be involved in analogical problem solving, suppose in the previous example that the initial representation of the source had been "the bird *builds* its nest." However, since dogs do not build anything, this first representation of the source domain *bird:nest* must be re-represented (i.e. shifted) as "the bird *sleeps* in the nest", since when *bird* is mapped to *dog*, nothing can be found to fit the *build* relation. This flexible representation of the domains constituting an analogy is part and parcel of analogical reasoning (Gentner & Kurtz, 2006b; Kokinov, Bliznashki, Kosev, & Hristova, 2007). However, the re-representation process, we believe, has cognitive costs in the sense that it is sometimes strategic (one has to understand the need to revise an initial representation and then find another interpretation of the pairs). Executive functions (inhibition and flexibility) are, therefore, required in analogical reasoning. The experiments presented in this chapter investigate the consequences of re-representation.

If inhibition and cognitive flexibility are involved in analogical reasoning, as argued above, a procedure focusing children's attention on and anchoring their representation of the AB pair might negatively affect their performance. This could occur, for example, when children first focus on a relation that will make no sense in the analogy. They might get "stuck" on this first representation and, because of their lack of cognitive flexibility, they might fail to re-represent the AB pair and find the relation allowing a consistent analogical mapping. Thus, using stimuli with an additional, irrelevant interpretation for AB should lead to poorer performance compared to a case in which there is no such a priori incorrect interpretation of AB or in which the correct relation is given at the onset of the task. Experiments 1 and 3 presented in this chapter were designed to test the role of cognitive flexibility while reasoning by analogy, and Experiment 2 to create a procedure that alleviated extraneous cognitive costs of the A:B::C:? task and to help them focus on their AB interpretation.

II. Experiment 1: Re-representation in analogical problems

II. a. Objectives and hypotheses

This first study was designed to assess children's ability to use prior information efficiently to solve a subsequent A:B::C:? problem, that is to use prior representation of part of the problem if it is relevant or to shift it if necessary (cognitive flexibility being one core executive function). To test their ability to re-represent the problem space, they were given an irrelevant relation for the solution of the A:B::C:? task before being shown the problems (Re-representation condition). In another condition (Facilitation condition), they were given the relevant relation prior to the problem to assess the possible benefits of having information a priori. To do so, we used two supplementary pairs of pictures. We compared these conditions to a third one in which empty frames were shown before the analogical problems (Analogy condition), that is without induction of any relation prior to the problems. The number of distractors (one) was kept constant throughout all these conditions and the AB pairs were chosen to have two different relations possible between A and B to allow it to be interpreted with the relevant or the irrelevant relation given before the A:B::C:? problems.

The experiment thus followed an Age (5-to-6-year-olds, 7-to-8-year-olds) x Condition (Analogy, Facilitation, Re-representation) design with the Condition being a within-subject factor. We measured response accuracy and reaction times.

We hypothesized that Re-representation trials would need more cognitive flexibility than Analogy trials, and that Facilitation trials would require less cognitive demands to children than the others types of trials, because crucial information was given before the problem being displayed. Thus, our predictions were that younger children would have lower performances than older children, that the Re-representation in which children would be given an irrelevant relation to solve the problem would lead to lower performance than the Analogy condition in which no relation was given, and that the Analogy would lead itself to lower performance than the Facilitation condition in which the correct relation was given. We expected that the Reaction times would follow the same trend, with faster response in Facilitation trials, and slower response in Re-representation trials when compared to the Analogy condition, and overall slower answer for the 5-to-6-year-olds than for the 7-to-8-year-olds. As development of cognitive flexibility has been shown in preschoolers and older children in the literature (Chevalier & Blaye, 2006), we also expected a significant interaction between Age and Condition within those two dependant variables, with a lower effect of the Re-representation trials in 7-to-8-year-olds children than in 5-to-6-year-olds.

II. b. Methods

Participants

Twenty 5-to-6-year-olds (12 males, 8 females; M=70.5 months; SD=3.2; from 66 to 75 months) and 20 7-to-8-year-olds (10 males, 10 females; M=93.3 months; SD=5.3; from 79 to 101 months) participated to this study. Participants were allocated to any of the three versions of the task in equivalent group sizes and randomly. All of them were naïve to the task. Children's participation was submitted to parents' informed consent and children participated voluntarily.

Materials

The task consisted in 12 A:B::C:? trials: 3 training trials at the beginning and 9 test trials following them. Each participant was tested in the 3 different conditions (i.e., Analogy, Facilitation, and Re-representation conditions). There was 1 training trial, and 3 test trials for each condition. The 3 training trials on one side, and the 9 test trials on the other, were presented randomly, with training trials at the beginning of the task.

Three versions of the tasks were designed (A, B and C), following a Latin square: the trials in the Analogy condition in version A became Re-representation trials in version B and Facilitation trials in version C. The same was done with the others conditions resulting in every trial being presented in the three conditions across versions. This allowed us to control eventual item effects.

The AB pairs were chosen to have two potential and distinct relations linking them. For example, the pair "*snowy landscape:sun"* contains the *"melted by"* and *"lit by"* relations. The relation between A and B being equivocal, the participants had to search information from C and the solution set in order to interpret correctly the AB pair and chose the correct answer.

Every trial of the Analogy condition was built out of 7 black and white photographs (220x220 pixels; embedded in a black frame) corresponding to the A, B, C, T, one Dis and two U terms of the analogical problems. A, B and C, and a black empty frame were displayed at the top of the screen in a row. The solution set (T, Dis and 2 U) was displayed in a row at the bottom of the screen.

Facilitation and Re-representation trials were preceded by two pairs of black and white photographs screen (220x220 pixels; each appearing in a black frame) in a row at the top of the screen, A1:B1 and A2:B2, which were linked to the A:B::C:? problem of either of this manner: in the Facilitation condition, the pairs preceding the analogical problem were linked by the same relation as the relevant relation for solving the problem and completing the C:? pair, or, in the Re-representation condition, the pairs preceding the A:B::C:? problems were linked by the relation that also linked the AB pair but that was not relevant for the solution of the problem and the completion of the C:? pair. Following the same example than above, the *"snowy landscape:sun::desk:?"* problem was preceded by *"street:street lamp"* and *"tent:flashlight"* in the Facilitation condition (the relation being *"lit by"*), and by *"sugar:coffee"* and *"butter:pan"* (the relation being *"melted by"*) in the Re-representation condition. In the Analogy condition, the problems were preceded by empty black frames. The pairs preceding the problems were displayed two by two in order to make participants compare them and transfer the relation inferred in one pair to the other (see Figure 35 for a schema of the problems in the three conditions). The presentation of A1:B1 and A2:B2, and of A2:B2 and AB was followed by the A:B::C:? problems, presented exactly in the same way as in the Analogy condition.

The task was displayed using the E-Prime software (version 2.8.0.22) on a 17" élo 1715L touch screen (resolution: 1024x768) in order to record participants' answers and reaction times. Data were analyzed with Statistica 8.

Procedure

The experiment took place in a quiet room in children's schools and participants were tested one at a time.

Participants' recognition of the pictures used for constructing the problems was first assessed to insure that failure was not due to an inability to recognize some pictures. Each picture was presented alone and participants were asked to name it. In case they were not able to give a proper label, the experimenter noted the failure to give a name to the object and children were asked if they knew how it was used or where they could find it. If they could not, the

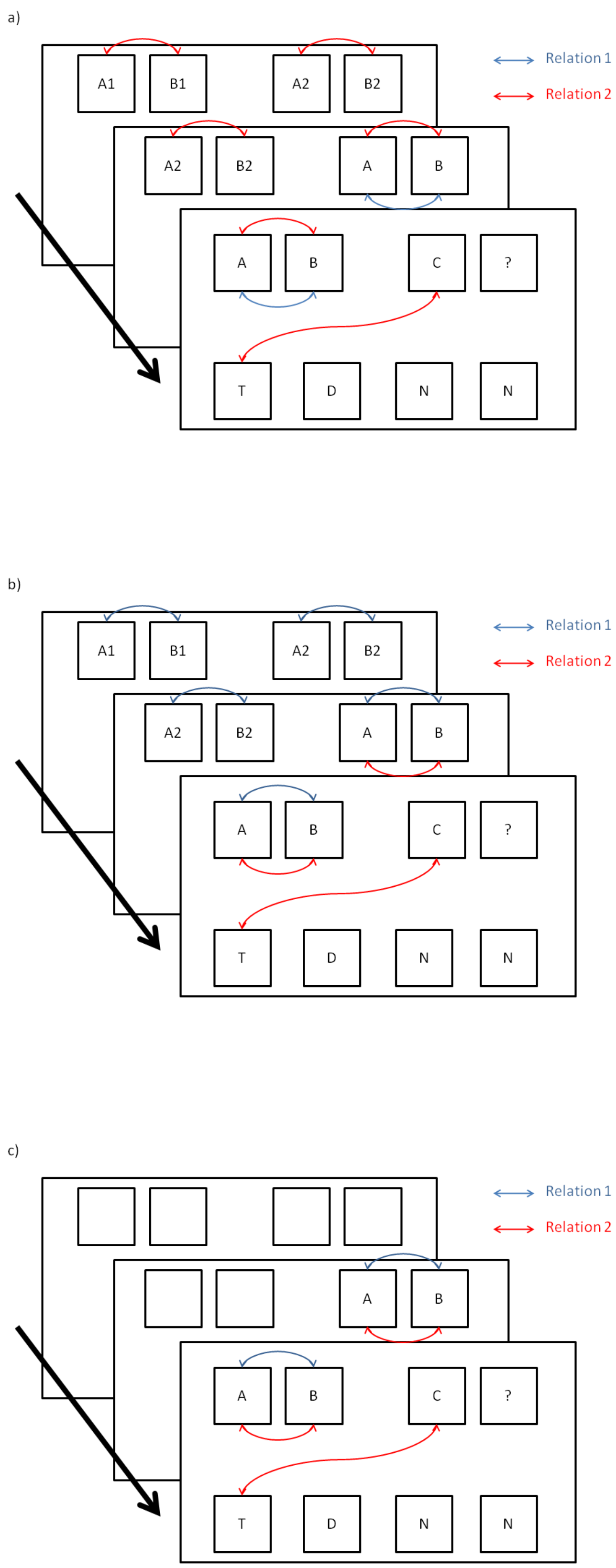


Figure 35: Presentation of the problems in the three conditions. a) Facilitation condition. b) Re-representation condition. c) Analogy condition (D=Distractors; N=Unrelated).

experimenter noted it and gave them the name of the object on the picture and a short description of what it was/how it was used.

After this first phase, the analogical reasoning task was presented on the touch screen. During the training phase, subjects faced the 3 different conditions through the three training trials. During the Facilitation and Re-representation trials, participants had five seconds to give the relation between the A1:B1 and A2:B2 pairs. In the case of an incorrect answer or of an absence of answer within 5 seconds, the relation linking A1:B1 and A2:B2 were given by the experimenter using the same formulation for both pairs in order to emphasize that they were identical. If the participant gave the correct relations linking the pairs, the experimenter confirmed these relations by using the same label for the two relations on the screen. After this, the experimenter made the A2:B2 and AB (the pair constituting the first part of the problem) pairs appear on the screen and the same procedure was applied as with the A1:B1 and A2:B2 pairs. The A:B::C:? task was explained as described in Chapter II. Participants had to press on the answer they wanted to give and were instructed to do so as soon as they had found the correct answer. Then they were asked to justify why they had chosen this answer.

In a third phase, participants knowledge of the relations between all the AB and CT pairs used in the task was assessed by presenting them individually to exclude the trials that were failed because participants did not know these relations, thus keeping only the trials failed because children could not reason by analogy. If children gave the relation between AB which was irrelevant for the solution of the problem, they were asked if another relation linking the two pictures existed.

II. c. Results

More than 98% of the individual pictures were recognized during the first phase of the procedure. Fourteen out of 360 trials (3.8%) were removed because of the lack of knowledge of the relation linking at least one of the two pairs constituting the A:B::C:? problems. Thirteen were trials from the 5-to-6-year-olds group, 1 from the 7-to-8-year-old group.

Performance scores were analyzed using a two-way mixed-ANOVA with Age (5-to-6-year-olds, 7-to-8-year-olds) as a between subject factor, and Condition (Analogy, Facilitation, Re-representation) as a within subject factor (see Figure 36). The only significant effect was a main effect of Age ($F(1,37)=42.8$; $p<.001$; $\eta^2_p=.54$). There was no main effect of Condition (albeit there was a trend toward significance; $F(2,74)=2.8$; $p=.07$; $\eta^2_p=.07$) or interaction between Condition and Age ($F(2,74)=.6$; $p=.55$; $\eta^2_p=.02$).

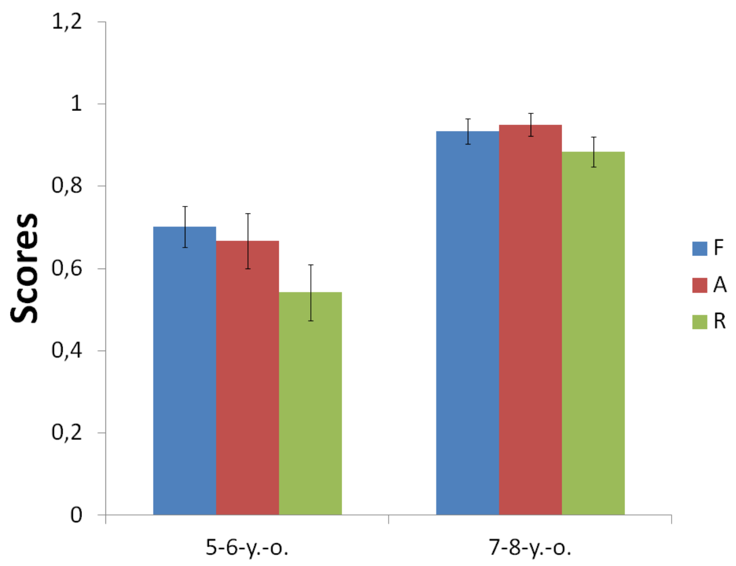


Figure 36: Performance scores according to the age of the participants and the condition (F: Facilitation condition, A: Analogy condition, R: Re-representation condition; error bars represent SEM).

Reaction times were also analyzed using an ANOVA design equivalent to the one used with Performance Scores (see Figure 37). It revealed no significant main effect, either of Age ($F(1,37)=.5$; $p=.50$; $\eta^2_p=.01$), or of Condition ($F(2,74)=2.3$; $p=.11$; $\eta^2_p=.06$), but there was a trend toward a significant interaction between the two factors ($F(2,74)=2.4$, $p=.09$, $\eta^2_p=.06$).

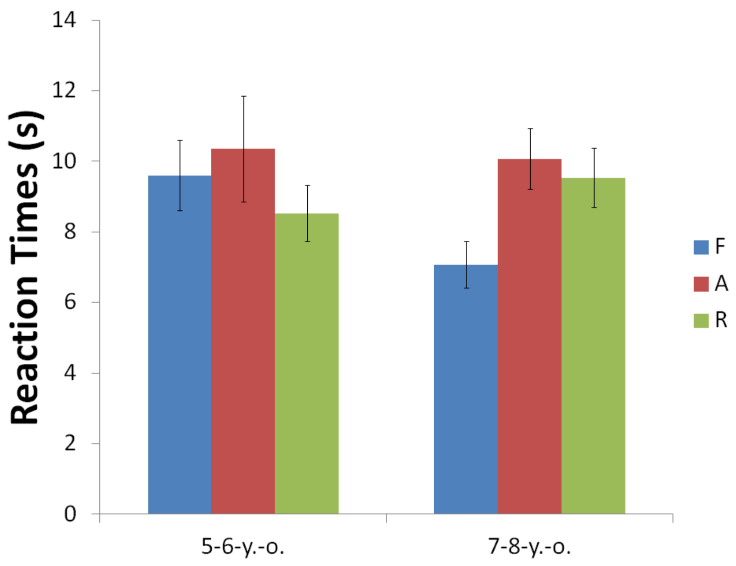


Figure 37: Reaction times of 5-to-6-year-olds and 7-to-8-year-olds in the three conditions (F: Facilitation condition, A: Analogy condition, R: Re-representation condition; error bars represent SEM).

However, when analyzed separately, Condition appeared to modify 7-to-8-year-olds' reaction times. A Tukey HSD post-hoc analysis run on 7-to-8-year-olds data alone showed a significantly faster response in the Facilitation condition (p=.005) than in the Analogy condition, and a significantly slower response in the Re-representation condition than in the Facilitation condition (p=.024), but no difference between Re-representation and Analogy trials (p=.824), as can be seen on Figure 37.

II. d. Discussion

The only hypothesis that was confirmed by our results was that older children would outperform younger ones. However, the trend toward significance of the interaction between Age and Condition and the fact that 7-to-8-year-olds reaction times were significantly affected by the condition when tested post hoc suggests that older children where indeed affected in their search for a solution by the induction of a relevant relation (faster answers) before the problem was presented. This result might not have appeared in scores because older children had near-ceiling performance, revealing the task was indeed too simple for them whatever the condition was. Results obtained in 5-to-6-year-olds showed absolutely no effect of the condition on the scores or the reaction times.

This discrepancy between younger and older children might be explained by two, related hypotheses. First, the intrinsic complexity of the task in terms of sub-goals might have prevented 5-to-6-year-olds to understand fully that they had to, and in what terms they should, relate the first (induction of a relevant or irrelevant relation) and the second phase (solving the A:B::C:? problem) of the task because of low executive functions resulting in difficulties in planning the task and making relations between subgoals (Diamond, 2013). Thibaut, French, Missault, Gérard, & Glady (2011) observed similar difficulties of preschoolers with a simpler task: they had difficulties even integrating one pair to their search of what went with C in the standard A:B::C:? problems. Second, the relation might not have been salient enough to cause any problem to young children. Thus, once the first phase ended, the induced relation was forgotten and never reactivated because of its low saliency. Another related problem was the small number of training trials in general, and particularly in the facilitation phase, that might have prevented children from seeing the potential benefits of using the relation induced for the solution of the next phase of the task. The next experiment presents a procedure designed to alleviate the cognitive load of the A:B::C:? task in terms of goal maintenance. This procedure was used in the third experiment of this chapter which addressed the question of the involvement of cognitive flexibility in children's analogical reasoning, and with a salient competing relation.

III. Experiment 2: Effect of seeing AB before the remaining pictures of the problem

III.a. Objectives and hypotheses

Starting from the empirical observation that children do not spend as much time as adolescents and adults on the AB pair (Thibaut, French, Missault, et al., 2011), this experiment assessed a new procedure’s ability to help children overcome their tendency not to search for crucial AB information. This procedure was designed to help children integrate the relation between A and B in their search for the analogical solution by countering their tendency to engage in the main goal of the task (i.e. finding something that is related to C), thereby overlooking this crucial subgoal.

We compared two groups of 5-to-6-year-olds in a between-participants design with Procedure (Standard, AB-first) as a between-subject factor. In the Standard procedure, all the stimuli appeared on the screen simultaneously. By contrast, in the AB-first procedure the A and B pictures appeared before C and the four possible solutions. In addition, in the latter procedure, the relation between the A and B pictures had to be verbalized before the remaining pictures appeared on the screen. We only measured children's scores in these two conditions.

We hypothesized that this procedure would help them to integrate A and B with the other stimuli involved in the task (C and the solution set), thus predicting that this procedure would elicit better performance than the Standard one.

III.b. Methods

Participants

Participants were 52 5-to-6-year-old children (mean age=67.6 months; SD=4.8; range: 58 to 77 months). Parental informed consent was required for the children to participate to the experiment and children were willing to participate to the experiment. All of them were naïve to the A:B::C:? task.

Participants were allocated randomly to two groups that were tested with the different procedures: 26 children were tested in the Standard Procedure (13 males, 13 females; mean age=67.9 months; SD=4.6; range: 58 to 75 months) and 26 children were tested in an AB-first Procedure (16 males, 10 females; mean age=67.2 months; SD=5.0; range: 59 to 77 months).

Materials

Materials for the two groups were identical and consisted of a set of 14 trials of an A:B::C:? task: 2 training trials, followed by 12 experimental trials presented randomly. Seven black-and-white drawings (240x240 pixels) constituted each trial, namely the A, B and C items, the T, one Dis, and two U, presented in a black frame. Training and test trials were presented in the same manner.

In the standard condition, the A, B and C pictures were presented in a row at the top of the presentation screen along with an empty black square where the answer would go. The four potentials answers were presented in a row at the bottom of the presentation screen.

In the AB-first condition, the AB pair was displayed alone on the screen (where they usually appeared in the A:B::C:? problems) until the participant verbalized a relation linking A and B. After participants' verbalization, all the stimuli were displayed as in the Standard condition.

The association strength between the pairs constituting the analogies was controlled. Six of the experimental trials consisted of weakly associated AB, CT and CDis pairs of pictures, the remaining six trials were made up of strongly associated pairs. Thus, the Related-to-C Distractor and the Target were selected to be equally associated with the C term. The strength of association was assessed by 13 students of the University of Burgundy who were asked to rate on a 1-to-7 scale, 1 being the lowest and 7 the highest, how much seeing one picture of the pair made them think of the other member of this pair. Experimenters gave explicit indications to students not to rate whether any relation between the two pictures existed, but if the two pictures were associated in their mind. The weakly associated items had a mean association strength of 2.84 for the AB pairs ($SD = 1.51$, range: 2.33 to 3.62), of 3.03 for the CT pairs ($SD = 1.75$, range: 1.87 to 4.46) and of 3.31 for the CDis pair ($SD=1.52$, range: 2.27 to 4.42). For the strongly associated items, the mean association strength for the AB pairs was 6.23 ($SD=1.01$, range: 5.08 to 6.66), 6.07 for the CT pairs ($SD=1.09$, range: 4.38 to 6.38) and 5.20 for the CDis ($SD=1.53$, range: 3.08 to 6.43). Association strength was significantly higher in the strongly associated than in the weakly associated pairs (bilateral Student t-test: $t(24)=6.73$, $t(24)=5.32$, $t(24)=3.16$; $p<.001$ for AB and CT, $p<.01$ for CDis).

These trials were presented on a 17'' élo 1715L touch screen (resolution: 1024x768) using the E-prime software (version 2.8.0.22). Data were analyzed using Statistica 8.

Procedure

The experiment took place in a quiet room at the children's school and participants were tested one at a time.

Participants' knowledge of the images used in the different trials was tested in order to ensure that incorrect answers were not due to an inability to recognize a particular item. Each stimulus was introduced alone and participants were asked to name it. If they could not name an item, they were asked if they knew how one could use it or where one could find that kind of item. If the child did not seem to recognize the item, its name and a short description was given by the experimenter.

After this recognition assessment, the experimenter tested the two groups with two different procedures for the analogical reasoning task. The Standard Procedure group was presented with the seven images at once (i.e. A, B, C, and the four possible solution items). The experimenter gave the participants the same instructions as presented in chapter II for the Standard A:B::C:? task.

In the AB-first Procedure (see Figure 38), children were given the same instructions as in the Standard Condition but were first presented with the AB pair alone and asked to verbalize the relation between A and B. Once they had given their interpretation of the AB relation, the experimenter revealed the five remaining pictures, so the children could see all seven images on the screen. From this point on, the procedure was identical to the Standard Procedure.

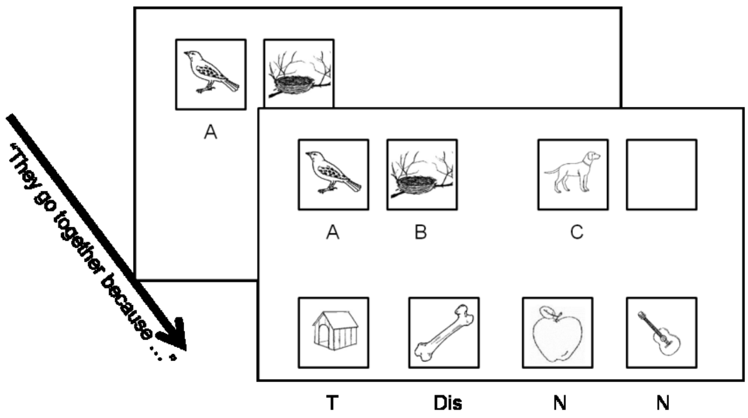


Figure 38: Design of the AB-first Procedure. The "A", "B", "C", "T", "Dis" and "N" (i.e., Unrelated) were not displayed during the task.

Finally, the experimenter assessed participants' knowledge of the relations holding between A and B, and C and T. All trials that were failed due to an absence of a participant's knowledge of the relations used to construct the analogy were excluded. We did not include trials that had been failed because children could not recognize the relation between A and B or between C and Dis.

III.c. Results

Overall, less than 2% of the stimuli were not recognized during the assessment of children's knowledge of the items used to construct the analogies. Twenty-seven trials out of 624 (4.3%) were excluded from subsequent analysis because the relation between A and B or C and T were unknown to the participants.

An independent samples two-tailed t-test was used to compare the performance scores on the AB-first and the Standard procedures. It revealed a significant difference between the two procedures ($t(49)=2.81$; $p=0.007$; $\eta^2_p=0.14$) with higher scores for the AB-first Procedure than for the Standard Procedure (see Figure 39), thus confirming the hypothesis that the AB-first procedure helped children overcome their tendency to not take into account the AB pair in their search for the solution.

The effect of the new procedure seems due to attentional emphasis put by the AB-first Procedure on the AB pair and its semantic interpretation, not to the correctness of the first interpretation in itself. Children's interpretation of the AB pair was not always correct (32 trials out of 312). Nonetheless, when they initially chose an irrelevant relation between A and B, they still found the correct answer 88% of the time (28 out of 32). In addition, they did not give the correct answer systematically when they interpreted the AB pair correctly. They answered incorrectly on 30% of these trials (93 out of 312). Thus, even when the representation of the AB pair was correct and the relation between C and T was known, children's reasoning could be disrupted. In consequence, these necessary prerequisites to efficiently solving the problems do not seem to be sufficient for success.

Overall, when children did not choose the analogical answer, they selected the Related-to-C distractor 87% of the time. Changing the procedure for the test did not affect their tendency to select the Related-to-C distractor, as there was no significant difference between the two groups in their tendency to choose it among the different distractors when the correct analogical solution was not chosen (independent-samples bilateral t-test: $t(49)=0.44$; $p=0.40$, $\eta^2_p=.004$).

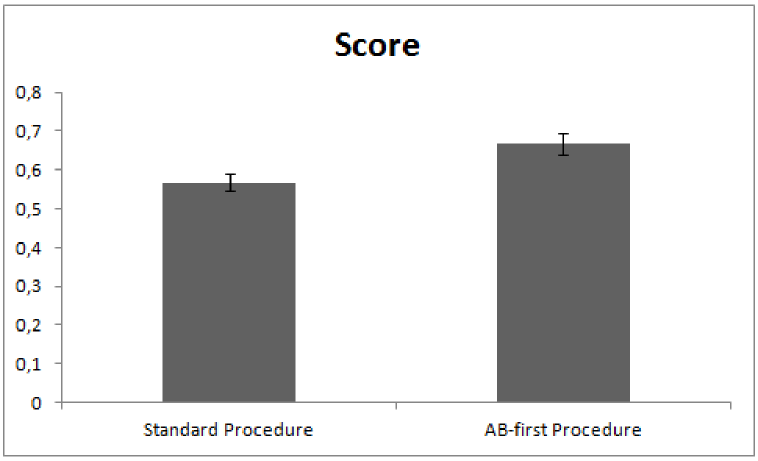


Figure 39: Performance scores obtained by children using the Standard and the AB-first procedures (error bars indicate SEM).

III.d. Discussion

This experiment was designed to assess the effectiveness of a new procedure to facilitate children's integration of the AB information when solving the A:B::C:? problems. Our results are consistent with the hypothesis that when children had to search for the relational information between A and B before seeing the entire problem, they performed better than children tested with the standard procedure (i.e. showing them the whole problem without asking them to verbalize the relation between the AB pair).

These results are consistent with results of Thibaut, French, Missault, et al. (2011) which showed that children focused on the C term and the possible solutions. Both sets of results can be interpreted in an executive-function framework, and, specifically, within an inhibition framework. One explanation for children's difficulties with the task would be that they have difficulties (temporarily) inhibiting the explicit goal of the task, and thus neglect the subgoal of finding the relation between A and B. In other words, they cannot temporarily detach themselves from the main goal (i.e., finding something that goes with C), and, therefore, they have difficulty focusing on the AB subgoal that is necessary to find the correct solution to the problem. Thus, they directly search for what is related to C, which leads to semantically-related errors. In this experiment, results show that, when provided with help to apply a more efficient strategy (i.e., explicitly focusing on the AB pair), children perform better in their search for the solution than in the standard procedure. Their difficulty in maintaining explicit goals has been reported elsewhere and was reduced when they were asked to verbalize the information related to a subgoal of the task (Blaye & Chevalier, 2011; Gruber & Goschke, 2004). Thus, seeing A and B and verbalizing the relation between them could help children because they do not need to generate this subgoal spontaneously.

Theoretical accounts have often emphasized the dependency of analogical reasoning on knowledge increase (Brown, 1989; Gentner & Rattermann, 1991; Goswami, 1992; Vosniadou, 1989). For example, the relational-shift hypothesis (Gentner & Rattermann, 1991; Gentner, 1988) claims that young children first focus on similarities between items. Later in development, a relational shift occurs, leading to the ability to focus on the similarity between relations. Our experiments provide support, in addition, for an executive-function explanation. Indeed, even though children know the relations constituting the analogical problem presented, they tend to have difficulty planning their search for information that goes beyond a simple matching of a Related-to-C image. In short, they tend not to seek the relational information from the AB source pair. The effect of familiarity with relations — and the resulting ease of using them — could explain the domain dependency of the age at which the relational shift occurs. In tasks of equivalent complexity, more familiar domains would lead to earlier solution on developmental time.

However, the maturation of executive functions could explain why children master the formal A:B::C:? task relatively late in development, regardless of the type of material used (semantic, abstract; Thibaut et al., 2010a, 2010b), whereas other, more “ecological” analogical problems are solved earlier (Goswami, 1992; Singer-Freeman, 2005). Even though they have the relevant knowledge to construct a correct analogy, planning and goal representation abilities might not be developed enough in preschoolers to handle the complexity of the strategy required to solve A:B::C:? problems effectively. In this task children have to infer the relation in the source domain, in addition to mapping the elements between domains in order to complete the second pair. Solving strategically complex analogical problems, such as A:B::C:? problems, might thus rely more on meta-cognitive skills such as planning and goal representation.

Using the AB-first procedure that was especially built to decrease the cognitive load of the task, the next experiment tried to react to the limitations of Experiment 1 and appropriate materials in order to make the irrelevant relation salient for children. In addition to this, children saw only training trials in which the salient relation between A and B was beneficial for solving the A:B::C:? problem.

IV. Experiment 3: Re-representation using a salient irrelevant relation

IV.a. Objectives and hypotheses

The failure of Experiment 1 of this chapter could be explained by different flaws in the ability of the former task to induce an irrelevant representation for the AB pair of analogical problems. The present experiment was designed to get rid of these flaws by decreasing the complexity of the task, by using a salient competing relation and highlighting the relevance of this relation throughout the task. In this experiment, we included AB pairs that could be interpreted in terms of two relations on two different dimensions (i.e. color relation and a semantic relation). In the previous experiment, 5-to-6-year-olds were not affected by the induction of an irrelevant relation before solving analogical problems. This can be explained by the intrinsic complexity of the task and by the low saliency of the irrelevant interpretation of the AB pair. However, we hypothesized that this would change when the AB pair would have a salient relation, but one that is irrelevant to the solution of the analogy problem. Children might initially attend to this irrelevant dimension between the A and B pictures and, since preschool children have well-known difficulties in switching their dimension of search (Blaye & Chevalier, 2011; Garon, Bryson, & Smith, 2008; Zelazo, Muller, Frye, & Marcovitch, 2003), we expected that they would tend to remain with their initial representation of the AB pair, rather than switch to the representation that was appropriate to the solution of the problem.

The present experiment used a within-participants design, with Type of trials (Color/Semantic/Mixed trials) as the only factor, to study children's ability to overcome a first representation of the source on an irrelevant dimension. This was tested by giving children trials with different dimensions of interpretation for the AB pair: "color identity" in Color trials (A and B were of the same color, but with no plausible semantic relation between them; the analogical solution was a stimulus with the same color as C), "semantic relations" in

Semantic trials (A and B were of different colors, but were linked by a plausible semantic relation, and CT had the same semantic relation), and Mixed trials (where A and B were linked by both a semantic and a color identity relation; for the CT pair, only the semantic relation made sense of the analogy). In the Mixed trials, it was assumed that children would focus first on the salient color dimension (i.e. color identity) that was of no use for correctly solving the problem. Thus, for these trials to get the correct answer children had to shift from a “color” to a “semantic” representation of the AB pair, thereby making use of their set-shifting abilities. Consequently, any differences between Mixed and Semantic trials could be attributed to the children’s being stuck in a wrong initial representation of the relation between A and B.

We only measured accuracy in this experiment, predicting that the Mixed trials would lead to lower scores for the children than the Semantic trials, and that the Semantic trials would lead to more failure to find the correct answer than the Color trials, color identities being very salient for children (Alexander et al., 1987).

IV.b. Methods

Participants

Participants in this experiment were 23 5-to-6-year-old children (10 males, 13 females; M=69.4 months; SD=3.7; range: 63 to 76 months). Parental informed consent was required for them to participate to the experiment and were voluntarily participating. Every participant was tested with the AB-first Procedure presented in this chapter and were all naïve to A:B::C:? tasks.

Materials

The task consisted of 13 A:B::C:? problems, i.e., 2 training problems and 11 experimental problems. Each trial consisted of 7 black and white line drawings (240x240 pixels) for the A, B, C items, the T, one Dis and 2 U, each framed in a black square. An eighth black square was displayed beside the C item to symbolize the place where would go the solution of the problem. Each drawing was filled with a single color (red, blue, yellow, green, rose, red, brown or grey). The AB pair was displayed, followed, after an interpretation of the AB relation had been provided, by the remaining stimuli.

There were three types of experimental trials: three Color trials, four Semantic trials and four Mixed trials. The relevant relation between A and B in the Color trials was color, thus the solution was a picture which shared its color with the C term. The items were chosen to avoid any obvious semantic interpretation of the pairs. These trials ensured that color was a relevant dimension for interpreting analogies throughout the task. In the Semantic trials A and B had different colors, which meant that color was irrelevant for the analogy problem at hand. These trials were equivalent to the semantic problems in the usual A:B::C:? task. In the Mixed trials, however, the A and B were linked by a color identity and a semantic relation. A trial was designed in such a way that, when considering the C item and the solution set, only the semantic relation made analogical sense (i.e., there was no possible "same color" solution). See Figure 40 for examples of Semantic and Mixed trials. In order to ensure that children would not neglect "same color" as a possible solution during the experiment we always put one of the 3 Color trials between two trials of the other types (i.e., Semantic and/or Mixed trials). Counterbalancing was done by converting Mixed trials to Semantic trials and vice-versa for half of the participants.

Association strength was also controlled: 50% of the Semantic and Mixed trials were composed of weakly associated pairs, and 50% of strongly associated pairs as defined in the precedent experiment. Association strengths were rated by 11 students from the University of Burgundy in the same manner as previously described. For the weakly associated trials the mean association strength was 2.64 (SD=1.43; range: 2.33 to 3.01) for the AB pairs, 3.08 (SD=1.87; range: 1.87 to 4.46) for the CT pairs, and 3.51 (SD=1.55; range: 2.36 to 4.67) for the CDis pairs. The mean association strength for the AB pairs was 6.04 (SD=1.07; range: 5.08 to 6.26), 5.88 for the CT pair (SD=1.22; range: 4.38 to 6.13) and 5.23 for the CDis pairs (SD=1.70; range: 3.08 to 6.43), for the strongly associated trials. The association strength was significantly higher in the strongly associated trials than in the weakly associated trials (two-tailed Student t-test: $t(20)=6.31$, $p<.001$ for AB, $t(20)=4.85$, $p<.001$ for CT, and $t(20)=2.48$, $p<.05$ for CDis).

We used two different sets of Related-to-C distractors in two versions of the task to ensure a particular instance of a distractor did not make children choose it, but that their choice was effectively dependant on the association strength between C and the distractor. For example, in one version of the task, the related-to-C distractor was "*whiskers*" (the C term being "*cat*") and in the other version, it was "*dog*". The association strength between Cs and the first set of distractors (M=3.5; SD=1.57; range: 2.36 to 4.42 for the weakly associated trials; M=5.27; SD=1.79; range: 3.08 to 6.43 for the strongly associated trials) did not differ significantly from the association strength between Cs and the other set of distractors (M=3.10; SD=1.49; range: 2.82 to 4.67 for the weakly associated trials; M=5.14; SD=1.50; range: 4.38 to 6 for the strongly associated trials). This was confirmed by a two-tailed Student t-test: $t(194)=1{,}67$; $p=.1$; $t(180)=.52$; $p=.6$ for the weakly and strongly associated trials, respectively.

The task was presented on a 17'' élo 1715L touch screen (resolution: 1024x768) with the means of an E-prime software (version 2.8.0.22). Data were analyzed using Statistica 8.

Procedure

The procedure employed was strictly identical to the AB-first Procedure presented in Experiment II: children first saw the AB items and were asked to verbalize the relation between them. They then saw the entire problem.

IV.c. Results

Only 1% of the items presented in the first phase were not spontaneously labeled or described accurately. Two trials out of 184 (1%) were not analyzed due to a lack of knowledge of one of the semantic relations composing the analogies. We separated Mixed trials in which children spontaneously gave a semantic interpretation for the AB pair (23 out of 92 Mixed trials; 25%) and those in which children gave a spontaneous color interpretation (69 out of 92 Mixed trials; 75%). We only included the latter trials in the main analysis, since our specific hypothesis was that children would have more difficulties when re-representation was necessary. These trials have been designated "Incorrectly-interpreted Mixed" trials. Due to this separation, one participant was excluded from the analysis of the trials with incorrect AB interpretations because of an absence of incorrect response for the Mixed trials.

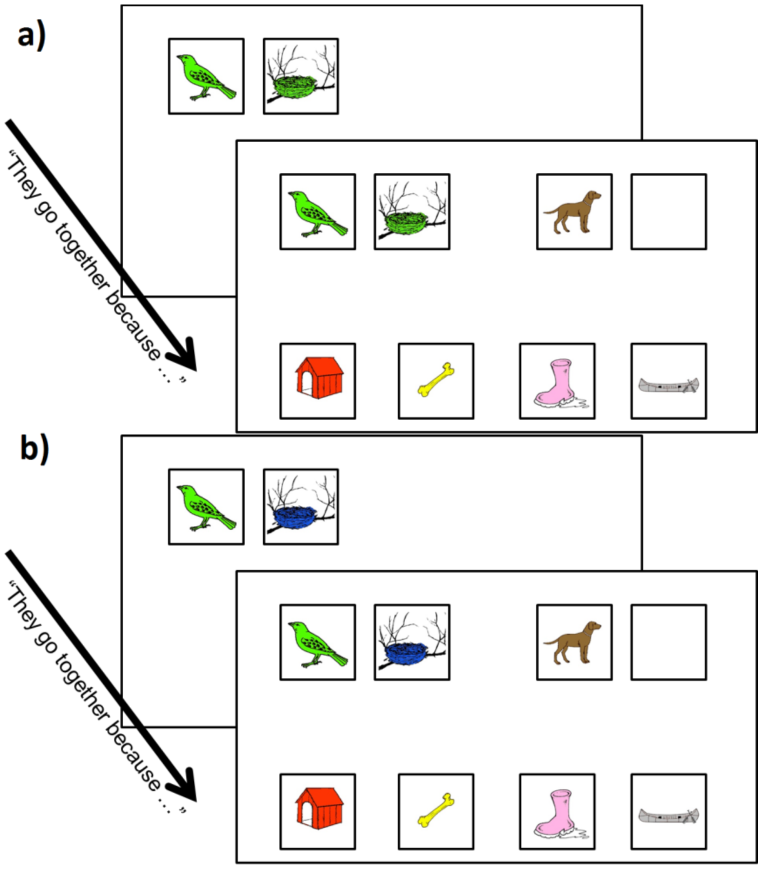


Figure 40: Examples of Mixed (a) and Semantic trials (b).

A one-way repeated-measures ANOVA was used to compare the Trial Types (Color/Semantic/Incorrectly interpreted Mixed trials, see Figure 41). It revealed a significant main effect of Trial Type ($F(2,42)=14.8$, $p<.001$, $\eta^2_p=.41$). A Tukey HSD post-hoc analysis confirmed that Mixed trials led to significantly lower performance (35% correct) than Semantic trials (55% correct; $p<.05$) and Color Trials (86% correct; $p<.001$). Color trials were solved better than Semantic trials ($p<.01$), confirming that this dimension was used when it was relevant. These results confirm children's difficulties in re-representing the AB pair once they have noticed the color dimension of the items. In 94% of the incorrectly solved trials, children chose related-to-C distractors when they did not find the analogical answer.

We also examined the scores for the Mixed trials that were spontaneously interpreted according to the relevant semantic dimension. The sample consisted of 14 children who spontaneously gave the semantic interpretation on 23 trials out of 92 (25%). The 9 remaining children systematically interpreted the AB pairs along the color dimension in the Mixed trials. The Mixed trials that received a spontaneous semantic interpretation (mean=.70, SD=.43) did not differ from the scores in the Semantic trials (mean=.61, SD=.28; related sample bilateral t-test: $t(13)=.78$; $p=.45$; $\eta^2_p=.045$). This suggests that children failed when they first chose the "same color" relation because they either failed to inhibit this first choice subsequently and/or because they could not describe the stimuli in terms of a novel relation. When they did not choose the correct answer, participants chose the related-to-C distractor 86% of the time.

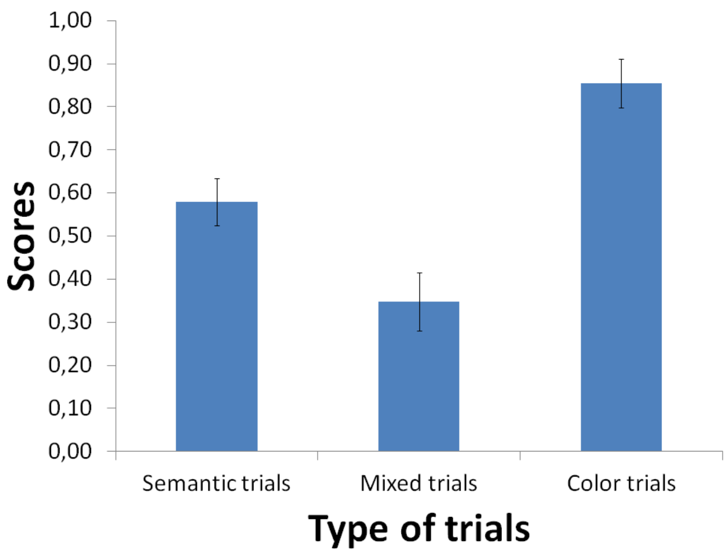


Figure 41: Performance scores in the Semantic and Mixed trials with the AB-first procedure (error bars indicate SEM).

IV.d. Discussion

Our results are consistent with the hypothesis that when children start interpreting the AB pair on a dimension that is irrelevant for the construction of the analogy, the emphasis put on the wrong dimension for interpreting A and B with the AB-first procedure is detrimental to children's ability to find the analogical solution. One interpretation of these results is that flexibility is needed when reasoning by analogy, especially when the domains involved are rich and have different potential dimensions of interpretation. At some point in the analogy process children who started with the wrong interpretation must find a novel interpretation of the relation between the items in the pair of stimuli.

It is noteworthy that when children did not start with an incorrect dimension, their reasoning was not disrupted by the identical colors of items as a criterion for matching. Their scores did not differ from the pure semantic trials.

V. General Discussion

Explanations of the development of analogical reasoning have recently included children's executive functions' maturation as a limiting factor, especially inhibition (Morrison, Doumas, & Richland, 2011). When the first experiment failed to show consistent evidence of the involvement of cognitive flexibility in analogical problem solving, most probably because of the complexity of the task and the low saliency of the competing relation, the second experiment showed that, when children first interpreted the AB pair on a dimension (the color interpretation) that did not allow them to make sense of the analogy, they were frequently not able to shift their search towards a more relevant dimension of the AB pair. By contrast, when there was no competing dimension in AB (i.e., no "same color" interpretation) their performance was better.

Overall, these experiments provide new elements in favor of the interpretation of children's difficulties in analogical reasoning as stemming from their incompletely developed executive functions.

Results from the third experiment illustrated set-shifting costs in children's reasoning: children's poorer performance when they first represent the relation between A and B along an irrelevant dimension can be explained by the fact that they cannot re-represent the relation between these items once they have found one interpretation of the pair. This representational fixity might be similar to the well-known impasse phenomenon in the problem-solving literature (Ash, Cushen, & Wiley, 2009). An "impasse" occurs when problem solvers have exhausted all paths in the problem space without finding a proper solution, given an initial inappropriate representation. This initial representation has to be replaced with a more appropriate one, which requires cognitive flexibility, to eventually solve the problem. However, our experiment does not distinguish strategy deficits (i.e., the inability to plan another exploration of the AB pair once the first attempt to find a solution, or, alternately, the inability to inhibit the first interpretation) from re-representation deficits (i.e., the inability to find a new representation of the relation between A and B). Whether or not children try to reinterpret the AB pair before choosing any Related-to-C item remains an open question. Further research (e.g., eye-tracking studies) might help resolve this issue: if children paid attention to AB again after their first attempt to solve the problem, this would argue in favor of a set-shifting interpretation as it would indicate unsuccessful attempts to reinterpret AB. However, if children did not come back to A and B *after* trying to find an answer with the same color as C and continued to organize their search around C, this would reveal an inability to change plan. However, if children paid attention to and tried to reinterpret the AB pair after the failure of their first attempt, their increase in error could be argued to be due to an inability to change their initial representation of the source domain. In other words, children's lack of flexibility could be detrimental at different levels (i.e. representation or strategy).

General Discussion

Chapter VI: General Discussion

I. Summary of the goals of this dissertation

Analogical reasoning is a complex activity, and, as such, the associated search for information has to be organized. The studies presented in this dissertation aimed at studying the organization of the visual search in and compare them to predictions from theories about analogical reasoning. It also aimed at observing the effect of analogical reasoning tasks differing in their goals on these strategies, and to study the interdependencies of analogical reasoning and executive functions, as these functions mediates the operations on information in a goal-oriented manner. This was achieved by the observation of adults and children in different tasks used in current analogical reasoning research to assess this ability that differ in the goals they elicit in participants. This was done at a specific level of analysis by the observation of the visual search of information through eye movements directed to the materials composing the tasks. The two tasks compared were the scene analogy task in which the participants is more directed toward the comparisons of different elements of the two domains compared on the basis of their roles, and the A:B::C:? task, which is more focused on the similarity relationship between the relations composing the two domains in themselves. It has been shown that the goals of a task indeed influence information gathering through eye movements (Yarbus, 1967), and current models of analogical reasoning indeed predict such effects (Holyoak & Thagard, 1989; Salvucci & Anderson, 2001). Thus, we expected that visual strategies would differ between these tasks, revealing their differences in goals at a perceptual, information gathering level. As children show goal neglect in their early years (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008a; Marcovitch et al., 2010), we also expected that this inability to maintain goals efficiently while solving the task would affect their strategy, and that this would be visible in their search for information, neglecting to attend to some information linked to constraints on the solution of the problem. We thus compared adults' and children's scanpaths in these two tasks.

It is not sufficient to maintain the goals of a task active to resolve a problem, it is also necessary to implement these goals as a treatment on the information which is gathered to effectively solve the problem at hand. This operation on the information toward goal achievement is handled by executive functions, the three most commonly acknowledged being inhibition, cognitive flexibility and working memory refreshing. Therefore, we expected that visual strategies in analogical reasoning tasks would reveal adults ability to operate on information. To do this, we manipulated the difficulty of the trials to put a higher load on these functions in difficult, more abstract trials than in easy, concrete ones. Indeed executive functions and their engagement in a task are dependent on the properties of the representations they operate on (Chevalier, 2010). Hence, this manipulation seemed appropriate to observe potential differences in the execution of the solution strategies, especially in adults. We also studied children's visual search in analogical task, because children are known to be more limited in their executive abilities than adults (Chevalier & Blaye, 2006; Garon et al., 2008). We expected that they would demonstrate visual strategies more influenced by information irrelevant to the task solution than adults, thus showing less control on the implementation of the strategies. We also studied the link between children's executive functions and cognitive flexibility especially, as this link was not backed up by extensive experimental evidence. This was done by using materials and a procedure especially designed for this purpose.

II. Differential effects of goals of the task on visual search

II. a. Mature visual search and goals

Visual strategies, even in adults, have not been extensively studied in analogical reasoning yet. In the studies presented in this dissertation, eye movement data converged to commonalities and differences between the different tasks commonly used to asses analogical reasoning. The scene analogy task put more emphasis on the mapping of elements on the basis of their roles in their respective domains. We observed that, at the level of eye fixations, participants focused on the elements of each domains that were related to the goal the task, i.e., the one which was pointed to in the source domain, and the one that had a corresponding role in the target domain. Other objects (i.e., Unrelated objects) composing the scenes were not fixated to a large extent. The most frequent saccades executed between elements were between the related elements in the source and the target, and between the element with an arrow in the source and the one that had a corresponding role in the target. Comparisons between the different elements in the target domain were not frequent, with the most frequent being between the correct answer and the distractor. However, aside from the direct mapping between the goal elements of the task, very few saccades were made between the two domains.

Gordon & Moser's (2007) study, described in the introduction, investigated visual search in the scene analogy task. Their main results were that the greater fixation times were allocated to the corresponding goal elements in the source and target domains, that the elements involved in relations were fixated longer than those which were not, that the distractor (perceptually similar to the goal element in the source in their case) attracted more fixations than an unrelated entity, and than control elements put at the same place in different trials. They also showed that participants studied more the source picture at the beginning of the trial, which is compatible with Thibaut, French, Missault, Gérard, & Glady's (2011) results and those with adults in easy analogical trials in our third chapter. Also of importance, for our account of goal directed eye behaviors in analogical reasoning tasks, their participants made more saccades between a third, extra object, when it was related to the two other objects that constituted the basis for the analogy than when this same object was not related to them. Additionally, they observed that their participants tended to compare distractors and solutions of the problems presented.

Overall their results are consistent with ours, suggesting that participants were more focused, during their information search, on the internal consistency between the entities in the same domain, related to the encoding and inference of the relations to form a structured relational representation of the two domains to be compared, but also the comparison of the source and the distractor. These results were stable even though the instructions Gordon & Moser (2007) used were the original, ambiguous ones (Richland et al., 2006), asking their participants to find what was like the object pointed to in the source in the target picture. This suggests an interpretation of these instructions by adults as involving relational similarity more than perceptual similarity. This difference in instructions might have had a greater impact on children's than adults' visual strategies. However they did not test children with this same procedure, thus not allowing the direct comparison of our results. Nonetheless, Gordon & Moser overlooked the importance of between domain saccades as they did not analyze them, arguing that the intra-domain saccades accounted for 52.3% of the total saccades. Our studies included the inter-domain as well as the intra-domain saccades and found subjective significance of the saccade mapping the goal elements in the source and the target domains, which we believe is an important result, and which we will discuss further below.

We also studied adult’s strategies in the classic A:B::C:? task with different types of materials: pictorial and verbal presentation of the terms, within or without scene presentation, with difficult and easy to infer and represent relations, and with different types of distractors. We found commonalities in all these studies: adult participants were mainly focused on the A, B, C and solution terms with a slight preference for B and T, without paying much attention to the related and unrelated distractors. However attention was still caught by related-to-C distractors more in this task than in the scene analogy task. The most frequent saccades were between the pictures representing the source and target relations (A and B, and C and T) and between the different potential solutions, with slight differences between the different variants of the task (i.e., more saccades between all potential solutions when presented in a verbal than in a pictorial form, and in meaningful scenes than in unrelated frames).

Bethell-Fox, Lohman, & Snow (1984) investigated the visual strategies of adults in geometrical analogical A:B::C:? problems. They found differences between high fluid intelligence and average fluid intelligence participants, and between easy and difficult trials, in the use of a strategy of construction of the response, and a strategy of elimination of the implausible answers. The solution construction strategy (i.e., constructing a hypothesis for the solution based on the knowledge of A, B and C) arose more frequently in simpler trials and in higher fluid intelligence participants, and the response-elimination strategy (i.e., finding the solution by eliminating the answer options that are not plausible) arose more in difficult trials and in lower fluid intelligence participants. These strategies were identified by the observation of the number of returns on A and B after seeing C and the solution set, the first alternative looked at, and the number of different alternatives observed. Another study using eye-tracking in this task was Thibaut et al. (2011) who also explored adult visual strategies in the A:B::C:? task, comparing them to children’s. Their main results with adults were overall fixations mainly distributed on A, B, C and T, with their participants first looking at the A and B terms then to the two other terms.

Bethell-Fox et al.'s (1984) analyses of visual strategies are quite different from those ran in the present dissertation. Due to these inherent differences, we cannot compare extensively our results and theirs on what type of fixations and saccades were favored by participants in the solution of the trials. However, we found commonalities in the differences between easy and difficult trials, in the type of strategy used by participants (i.e., constructive or response elimination), even though the materials used were verbal in our study. Our results are compatible with Thibaut et al. (2011) in that the fixations were more centered on the A, B, C, and solution items and less on the distractors. When we divided the trials in time slices we also found a first focus on the A and B terms in simple trials similar to those used in their study.

Commonalities and differences were found between the A:B::C:? and scene analogy tasks. Both tasks had common patterns of saccades. Participants in either the A:B::C:? or the scene analogy task spent a long time making saccades between the terms that were relationally linked within the source and the target domains, and also compared at least to some extent the solution and the distractor that was related in some way to the elements belonging to the relational structures to be compared. The first pair of saccades is most likely the mark of the encoding and inference of the relations between the elements compared. This is also suggested by the fact that, when measured, the encoding of the more complete (in terms of information that is given and does not have to be searched), source domain happens earlier than the encoding of the relations in the less known, target domain. Saccades between different potential answers, and especially between the related distractor and the correct answer is linked to the comparisons between these different answers on the basis of the constraints the task put on the solution, i.e., to have the same relation to C as B has to A. However the proportions in which these saccades were executed in the different tasks were different in adults, revealing different constraints of the tasks. The comparisons inside the target domain in general, and between the target and its related term were more frequent in the scene analogy task than in the A:B::C:? task. This might be because the scene analogy task presents the elements of the target domain together within a scene, in an obvious relation to each other (i.e., with pictures that depicts a movement). Another notable difference is that the scene analogy elicited more saccades between the goal objects in the source and target domain. This is of particular interest as the task explicitly instructs participants to compare and align these elements, when the A:B::C:? task do not. Another difference is the time spent looking at distractors which vary depending on the relevance of distractors to the goals of the task. Therefore, the two tasks seem to share the way the relations are encoded and the solutions are compared, but are modulated by specific goals.

Another effect we found that would be predicted by the goal management account was the fact that adults, if offered a choice allowing a cross-mapping in the A:B::C:? task (i.e., the opposite-relation distractors of chapter III), tended to make a great number of errors, even though they virtually did not make errors with related-to-C distractors by any other type of relation. This was explained by the inherent focus of the A:B::C:? task instructions on the similarity between relations, and not roles, between the solution and C on one hand, and between B and A on the other: participants focus on this similarity relation without taking into account the mapping between the elements of the two domains. Thus, even adults would exhibit goal neglect in the cases displaying distractors evoking relations strongly linked to the goal of the task.

Goal effects are predicted by two models of mapping: ACME (Holyoak & Thagard, 1989), and the path-mapping theory (Salvucci & Anderson, 2001). The first is a model of the mapping process on its own, and thus it is difficult to make predictions about the implementation of participants' search for information, as it describes purely internal operations made on representations that are already encoded. The goals of the subject affect this model by biases put on the mappings that are connected to his current goals, which could be used to simulate potential task effects by using these biases to influence the mapping and make it more focused on relational similarity, or on role similarity, between the two domains compared.

The ACME model also predicts a full alignment between the two domains compared. It is possible that this mapping is fully accomplished in working memory, without the help of a perceptual support, especially with such simple relational structures as those that were used in our tasks. Nonetheless, our data support a more pragmatic view of the mapping process itself, with only elements and relations that are relevant for the goal of the task explicitly mapped one on another and evaluated on the basis of corresponding roles. A way to further our answer to this question would be to overload working memory capacities of participants by using complex scenes while recording their eye movements, in a scene analogy task. If the mapping has to be fully accomplished, it is likely that all the elements which are involved in the relational structure of the two domains would be attended to a large extent, and that saccades between domains would be more common even between elements involved in relations not directly relevant to the main goal to alleviate the cognitive load of mapping two complex domains, thus using a perceptual support to refresh the correspondences stored in working memory.

By contrast, we would predict, together with the path-mapping theory, that there would be more intra-domain saccades, participants thus encoding the relational structures of the domains and determining the roles of the goal object in the source domain, and that the larger part of the inter-domain saccades would be between the goal elements in the two domains, or, if present, between the elements sharing similar roles in the two domains but violating other constraints on the solution like the systematicity constraint.

Another noteworthy fact we observed in our experiments is that differences appeared in the strategies used to solve goals specific to the different tasks. This could not be predicted by ACME because it is not embedded in a general problem solving architecture as the path-mapping theory is (Salvucci & Anderson, 2001). The path-mapping model predicts that different goals would terminate the solution process differently, as it is the information gathered to achieve the different subgoals of the task, subgoals which can be implemented specifically in face of the specificities of the different tasks that put the reasoning process to an end. When enough information has been gathered to activate the answering process of the model, the task is over. This model is also relevant as it would be able to simulate a partial mapping process between the two domains as long as there is enough information gathered by the system with this partial mapping to terminate the task.

As our data reveal, people do not stop exploring the scene while they are mapping one domain on another, but continue this exploration throughout the task. Hence, it is likely that all the visual behaviors that we recorded were not related to the encoding of the structure of the domains, but also to the encoding of information specific to the subgoal at hand, like the information necessary to discriminate different potential answers, perhaps on the basis of them belonging or not to the same category as the corresponding element in the source (Green et al., 2008), or to the comparison and evaluation of the similarity of the roles of elements under the focus of attention in the two domains, and so to achieve the mapping between the two domains correctly. This argues in favor of the encoding and mapping processes being interleaved, as Tabletop and Copycat (French, 1995; Mitchell, 1993) predicts. Thus, our results seem to support the path-mapping model in its predictions of how the task solution is implemented by participants, and also the architecture of Tabletop and Copycat in their interleaving of encoding and mapping processes.

To sum up, it seems inevitable that models designed to account for analogical reasoning processes in adults have to take into account the specificities of the tasks in terms of goals. This is mandatory not only for the simulation of fine-grained behavior like eye movements and information gathering in a task, but also at a more general level to account for errors made during analogical reasoning tasks.

II. b. Goals of the task and children's visual search

As goal neglect is frequent in children (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008; Marcovitch et al., 2010), it can explain that young children exhibit patterns of fixations and saccades in relation with the goals of the task different from those observed in adults. Indeed such differences were already observed between adults' and children's information gathering in an A:B::C:? task (Thibaut, French, Missault, et al., 2011). This study showed that children focused more on the target domain than on the source domain, and quite rapidly after the beginning of the task. On the contrary, adults first focused on A and B to a large extent, and then gathered information from the target domain. This difference might be due to discrepancies in the ability of children and adults to maintain the goal of comparing the relations between A and B, and between C and their answer, i.e., the constraint making a solution correct. Children might thus address a less complicated and easier to maintain goal: find something that is related to C, which would explain why they make more distractor errors than adults, distractors being related to C, but in another way than B is related to A. In our studies, we did not find any difference between adults and children in the way they handled the information coming from the A:B pair (especially AB saccades). It is possible that using several analogical reasoning tasks helped children to understand and maintain the goal in the A:B::C:? task because of a progressive alignment between the different tasks (Goswami et al., 1998; Kotovsky & Gentner, 1996), the two other tasks being simpler as it is suggested by children's higher performances. Still, although we did not replicate the differences observed between children and adults in the A:B::C:? task, modifying the procedure of this task to allow children to more easily address and maintain the goal of the task showed beneficial in preschoolers: when children had to look at the A and B pictures first, and to verbalize the relation between the two pictures, they exhibited higher performances than when they had the standard procedure with every picture at the same time and without having to name the relation linking A and B.

Another argument in favor of a goal neglect account for certain failures in analogical reasoning tasks in children come from the eye movement patterns in conjunction with patterns of errors in the scene analogy task. Our studies had findings convergent with those of Richland et al. (2006): children made more relational errors than adults in this task, i.e., they chose the other element involved in the target relation but that did not share the role of the element with an arrow in the source. This might be due to the neglect of a constraint on the solution of these problems: children might not align correctly the corresponding elements between the two domains, thus forgetting to compare their roles in the similar relations. This is further suggested by the fact that, contrary to adults in the same task, children do not make saccades between the corresponding items in the two domains compared. Hence, this type of saccades, only visible in adults, might reflect this process of evaluation of the similarity of the two elements (i.e., the solution, and the element pointed to in the source domain) in terms of roles.

As mentioned earlier, most theories about analogical reasoning development are vague about the mechanisms that allow the development of such abilities. The relational shift observed in children could be explained by a development of strategies that are used in the tasks, even if the knowledge accretion explanation is preferred (Gentner & Rattermann, 1991). The relational primacy account (Goswami, 1991, 1992) states that children are able to use relational similarity to solve problems from an early age on, but that qualitative aspects of this analogical processes change through time. Some of these qualitative changes might be due to strategic and metacognitive development, thus letting room for a goal management factor in the development of this ability. The last account of children's analogical reasoning development (the Relational Complexity Theory; Halford, Wilson, & Phillips, 1998; Halford, 1993) would state that analogical reasoning develops because working memory capacity develops. However this is still compatible with the effects of goal maintenance in children's development of analogy-making as the goal structure of a task has to be kept active in working memory while operating on the representations in working memory. Therefore, a limited working memory capacity might result in a competition between the refreshing of the representation under operation and the goal structure of the task, which could explain the failure of younger children to maintain the goals of the task when reasoning. This explanation might also explain why children make more relational errors with a greater degree of relational complexity (Richland et al., 2006). It would not be the relational complexity of the representations in itself that overloads the working memory capacity in children (children are able to handle ternary relations at the age of 5, but even older children, aged 6-to-7, make relational errors in this task) but the competition between the refreshing of these representations and the refreshing of the goals.

The path-mapping theory, we believe, could easily model differences in analogical reasoning development related to goal management. The goal structure that sets the order of productions of the model is not subject to retrieval in the current implementation of the path-mapping theory; only the representations of the structures of the two domains are. Allowing not only these representations but the different goals of the task to be retrieved or not, this modulated by the complexity of the goal (lower order goals in the goal structure would be easier to retrieve), and thus limiting the model's working memory capacity, would let room for errors related to goal maintenance akin to those made by children. For instance, in the A:B::C:? task, the higher order goal of comparing the relations that are active in working memory would only be triggered probabilistically, and thus would lead to sometimes the triggering of an answer due to a lower order goal achievement like finding something that is related to the C term, whenever its relation is similar to the one between A and B or not. Similarly in the scene analogy task, a response could be triggered when the lower order goal of finding an object involved in a relation in the target similar to the one depicted in the source, whenever the role is the same or not. ACME could not be manipulated that way because it does not have any goal structure governing the answering.

III. Analogical reasoning and executive functions

Goal management is inherently dependent on executive functions as these functions permit the necessary operations on information in order to perform a task: keeping active and updating the information stored in working memory, keeping inappropriate or irrelevant information from entering working memory, and actively trying to change the representation of a problem when it leads to a wrong, inappropriate solution, or no solution at all.

III.a. Executive functions in adults' analogical reasoning

The link between goals and executive functioning was visible in adults' information gathering in different ways in our experiments. First, the distractor in the scene analogy task was not considered as very informative by participants who made short fixations and few saccades between the distractor and other pictures. This was interpreted as due to the irrelevance of the distractor to goals leading to a lower attentional focus to the distractor, thus needing less inhibition to answer correctly. However, in the A:B::C:? task, distractors were more relevant to the goals of participants, as they were related to C in some way, echoing the emphasis of the instructions on finding something that goes with C. Hence, in the A:B::C:? task, participants made longer fixations on the distractors. Second, there was a difference between types of distractors in the A:B::C:? task: participants looked longer to distractors when they were oppositely related to C than when they were related to C, but this relation not sharing similarity with the relation between A and B. This similarity of relation, in addition to causing longer fixation times, also increased the number of errors of participants in comparison to the condition with the distractor related to C in any way. Taken together, these results suggest that the close relation between goals and their achievement is real and that goals will condition what type of information is found informative by the subject but also to what extent one will be able to deal with and to inhibit certain types of information.

A second factor that seemed to modulate the role of executive functions in participants was their ability to clearly represent the relations between the terms of the analogical problems and the structure of the problem. Indeed when items were judged difficult, thus causing more errors and most probably due to the abstractness of the concepts to be represented, participants had to display cognitive flexibility. Their gazes returned to A and B later in trials in comparison to easy trials, revealing the necessity to change their representation of the relation between A and B after having seen the set of potential responses and not finding any corresponding answer. This suggests that when there is a greater uncertainty on the solution due to, for instance, semantic factors such as imageability, people have to re-represent the source domain in order to find a representation of the whole problem that fits all the criteria of the task. Another finding related to this point is that our participants devoted more resources in executive functioning, especially inhibition when they were presented with A:B::C:? problems with a right-to-left order of the terms composing the problem: they made more saccades between the C term and the distractor in this order of presentation than in the left-to-right, classic order of presentation. Thus, when competing resources were engaged to represent a task correctly in an unusual manner of presenting it, less cognitive resources were available to participants to inhibit distractors irrelevant for the solution of the task, resulting in more attention allocated to this distractor.

These results are coherent with current views of executive functions as inseparable from their substratum (Chevalier, 2010): the recruitment of these functions in analogical reasoning seems to depend, on one hand, on the ability of the subject to represent the relational structures that are compared, and, on the other hand, on the constraints on the solution and the goals of the task which will bias the subject to attend to different information.

Most of the computational models presented in the introduction of this dissertation do not take into account executive functions, even those who acknowledge the role of goals in the solution of analogical problems. Indeed the path-mapping theory which puts goal as central to the procedural outputs of the model to perform the task do not say much about how execution of the goals are implemented. On the contrary, it takes for granted the execution of the goals, as they are represented as "if…then" rules: as long as the conditions for the execution of the procedure leading to the achievement of the goal are gathered, the result of the operation triggered by this rule is guaranteed. Thus, this model does not handle the kind of results reviewed above about differences of engagement of executive functions as a consequence of the ability to represent the structures compared. This is due to the fact that representations are handcrafted by the experimenters and are not built by the model itself, like in Copycat or Tabletop. The only model reviewed above that incorporates at least on component of the executive functions is LISA (Hummel & Holyoak, 1997), in which inhibition plays a great role in the ability of the model to represent the structures and to compare them. We saw in our experiments that the inability to inhibit some parts of the information (i.e., distractors) is concomitant to an increase in the number of errors. LISA would predict this as the lack of horizontal inhibition would lead to errors in the representations of the structures and of mapping, just like it is observed in participants. However, this model does not say much about the perceptual processes underlying the mapping process. Analogical reasoning in adults also seems to engage flexibility in the representation of domains compared. This flexibility is well captured by the architecture of Copycat and Tabletop, as new global representations of the problem can emerge from new incoming information and new lower-level structures.

III.b. Executive functions involvement in the development of analogical reasoning

The involvement of executive functions in analogical reasoning seems to evolve with time as these functions develop with age. Children are more prone to look at distractors, search and maintain their relation with C in working memory, and to select them as an answer, than adults. This was observed in all the tasks we used with children and adults. It suggests that their inability to maintain goal while searching for the solution has consequences on their ability to inhibit irrelevant information, thus making them look at these distractors and make distractor errors. Other evidence of differential engagement of executive functions between children and adults come from the variability of children in their scanpaths while solving analogical reasoning tasks when compared to adults, and by the fact that children, once anchored in an irrelevant representation of the AB pair, have problems finding the correct solution. Indeed, children's and adults' scanpaths were classified in distinct groups by a neural network on the basis of a measure of their difference that took into account the structures of their scanpaths, which indicates that they proceed in different ways globally, while searching information to solve the task. Moreover, cognitive flexibility seems to be involved in analogical reasoning, as children who have notable difficulty changing their representation over time when leading to incorrect responses (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008b) had difficulty in the A:B::C:? task when they first settled on a dimension appearing irrelevant for the solution of the analogical problems subsequently.

These results illustrate well the dependency of the engagement of executive functions on goal representation. As the goal is difficultly maintained, the distractor might not be represented as a distractor, and even as a correct answer (i.e., as fitting the criterion for the simpler goal substituted to the real goal of the task). Similarly, as children have difficulty maintaining the representation of the task's goals, it might be that the apparent lack of flexibility observed in children in the A:B::C:? task is due to the goal of finding something that completes a relation similar to the one between the source pair being replaced by a goal easier to maintain, finding something that is related to C. This would explain why the A and B terms of the analogy become irrelevant for children during the solution of the task. Thus, part of the executive failures observed in children might be due to ill-representing the constraints of the task. Therefore, children's difficulty could result from the inability to correctly connect the goals of the task with their representations and trigger the appropriate operations on these representations rather than from a deficit in the operations themselves. This would let the possibility that the development of executive functions might simply be the development of the ability to correctly represent and maintain the goals of a task, i.e., a procedural sequence executed on the representation to have an output.

IV. Perspectives

A logical follow-up of our study of visual strategies and their differences in the different tasks we used between adults and children, and a way to confirm differential effects of goals, using materials more controlled in their similarity, would be to make participants perform the scene analogy and the within-context A:B::C:? with the same scenes. It is indeed possible to use the scenes used to make the A:B::C:? task within a "natural" context to perform the scene analogy task, by simply changing the instructions and the place of the arrow from the target domain to the source domain. This would permit to overcome the inherent limitations due to the use of Richland et al.'s (2006) and our materials in the different tasks. The original scene analogy task materials show elements obviously interacting with each other (e.g., a cat chasing a mouse) when the materials we used for the A:B::C:? task only put the different elements in the same scene, without any obvious interaction between the elements. Thus, the relations between them still have to be inferred. Using the same materials in the two tasks would be a finer test of our hypothesis that goal of the task influences the visual strategies, controlling extraneous effects due to the presentation of the problems.

If goals are important in the solution of analogical reasoning, it would be interesting to study goal neglect, using it as an independent variable, in different population known to have differences in their ability to maintain goals, i.e., children and adults. A way of studying differences in goal management between children and adults, and the need of working memory capacity to maintain the goals active when solving the task, would be the following task: manipulating the working memory load due to the representation of the two domains and the goal activation as two independent variables. Varying the goal activation would be allowed by, for instance, manipulating the number of trials with literal similarity (i.e., resembling objects have resembling roles) in a session and measuring children and adults' reaction times and number of errors in cross-mapping trials, while keeping the total number of trials constant across participants with a varying number of filler trials constituted of true analogies (with only relational but not perceptual cues; see Kane & Engle (2003) for a similar manipulation of goal activation in the Stroop task). We would predict that even adults would show goal neglect with a sufficiently demanding working memory load, or with a sufficiently extinguished relational similarity goal. However, it would be important to unable the possibility to chunk information from the relational structures of the domains, chunking being an effective way to reduce this load (Halford et al., 1998). We would also hypothesize that children and adults would show goal neglect at different degrees of relational complexity. Another prediction would be that adult participants with different working memory spans would fail at different levels of relational complexity.

A possible way of testing the distinction between executive functioning per se (i.e., the possibility to use them efficiently) and their recruitment (i.e., their use when it is relevant to do so), dependent on goals, by children in analogical reasoning would be to use the task designed to test the involvement of cognitive flexibility presented in chapter V with an eye-tracking technology. If the failure in the task is due to a difficulty to execute a shift of representation, it is likely that children would look back to A and B, but would fail anyway. However if the relational similarity goal of the task leaves place to a simpler goal, they should not even look back to A and B, as these pictures would be irrelevant for this simpler goal of finding something that goes with C.

Other, wider perspectives would be to study the interaction between the differential cognitive resources recruited in executive functioning depending on the semantic properties of the materials more systematically. This perspective has not been studied extensively even though the theories of analogical reasoning, and especially of its development, do not deny the possibility of interactions between semantic knowledge and executive functions, but put the emphasis on either of these explanations being preponderant in the development, i.e., it is either semantic knowledge accretion, or the development of executive function and working memory that drives the development of analogical reasoning. Some semantic properties have already showed to be involved in analogical reasoning and to interact with executive functions in the solution of analogical reasoning tasks, like the association strength between the pairs (Thibaut et al., 2010b). In this dissertation, we saw that a possibility to explain the difficulty between our easy and difficult trials was the concreteness or imageability of the relations linking the different terms. Nevertheless, we did not test this hypothesis specifically. It has also been shown that the common categories between the elements mapped between the domains are activated during the reasoning process. However, we do not know how these different semantic factors cause a higher or lower recruitment of these functions, either in adults or children. For instance, if mapping is really guided by common categories between corresponding elements (Green et al., 2008), it is likely that base categories would be easier to activate and use as a guiding cue than superordinate categories, which include more disparate elements. Developmental studies would be of particular interest in the study of the interaction between executive functioning and semantic factors as both develop during childhood and adolescence, but not synchronously (Bird, Franklin, & Howard, 2001; Diamond, 2013; Mervis & Crisafi, 1982).

Perspectives shed by the present dissertation on the interaction between goals, executive functions, and representations, would be interesting to take forward by implementing them in a model. Neither of the models presented in this dissertation took into account these different factors at the same time, even though each model had strengths in the simulation of particular factors on their own. This would also be interesting to make the model able to be tracked in its fine-grained actions, i.e., to make it a production system, to test hypotheses and simulate phenomena about the interaction between goal management, executive functions and representation at different levels of observation, either subtler like eye movements, or rougher like response accuracy and reaction times. Necessary features of such a model, in order to comprehend these interactions, would be that it builds its own relational representations from the presentation of the materials, as Copycat and Tabletop do, that its working memory capacity would be limited, as LISA's working memory is, and that it handles goals which leads to differential triggering of operations on the representations built, like the path-mapping model does. Goal structure of the task and domain representations should be processed in working memory and able to be partly forgotten based on the competition between the loads these amounts of information put on working memory.

V. Conclusion

The findings presented in this dissertation suggest that goals modulate the recruitment of both executive functions and the perceptual system underlying the representation of the domains compared in analogical reasoning. Goal specific visual strategies were engaged in different analogical reasoning tasks, and goal neglects were shown to happen in children as well as in adults while solving these tasks. These different goals seem also to differentially engage executive functions in children and adults, as it is suggested in attention allocated to distractors, and returns to the source domain information. In addition to this, a possibility left open by the present results about children's ability to shift representation is that their difficulty to maintain goals throughout the solution of the tasks might explain their inability to engage efficiently executive functions even though they show the ability to engage it in other tasks. However, this remains to be tested systematically. Goal management and executive functioning was also shown to be differentially recruited in function of difficulty of trials, this difficulty most likely due to the level of ease to represent the relational concepts clearly, i.e., to have a representation of it that allows a clear-cut discrimination of potential solutions in the solution set. Taken together, these results suggest that goal management, executive function recruitment and representation interact in close ways. This interaction is not predicted by current models of analogical reasoning as no model includes these different parameters at the same time. Further studies and modeling attempts should thus study and simulate such interactions to give a more extensive account of how analogical reasoning is achieved in specific tasks, and how it develops during childhood.

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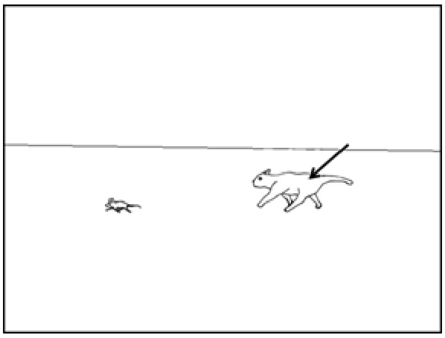
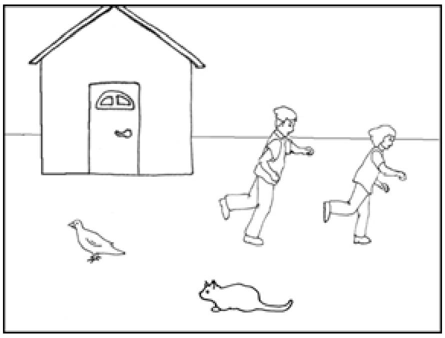
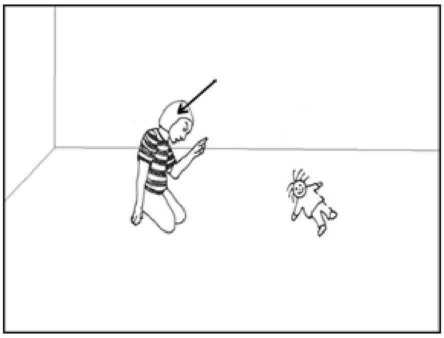
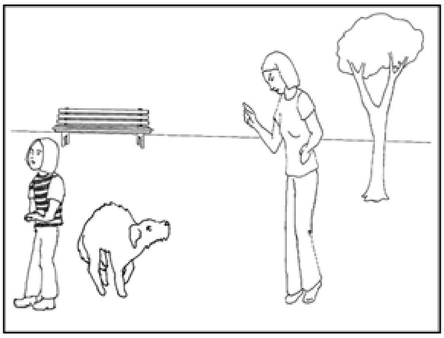
Annexes

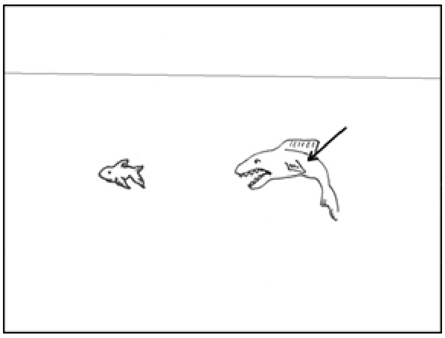
Annex A: Materials from experiment 1, chapter II

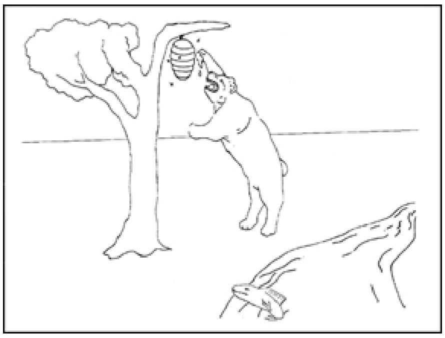


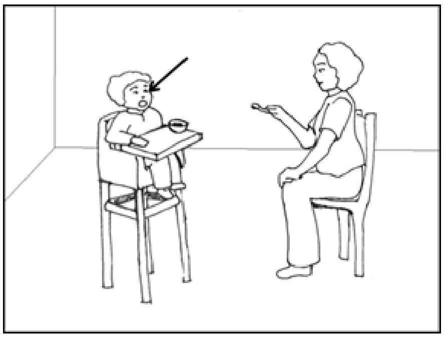


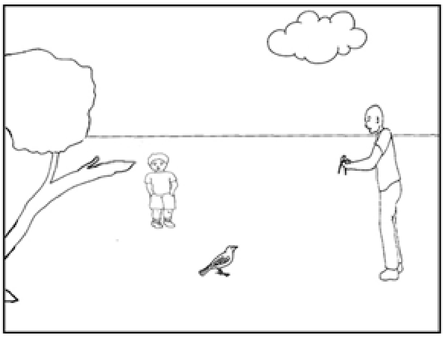












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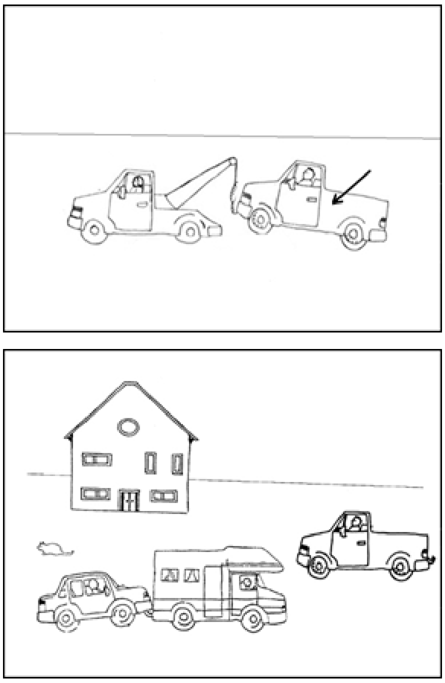
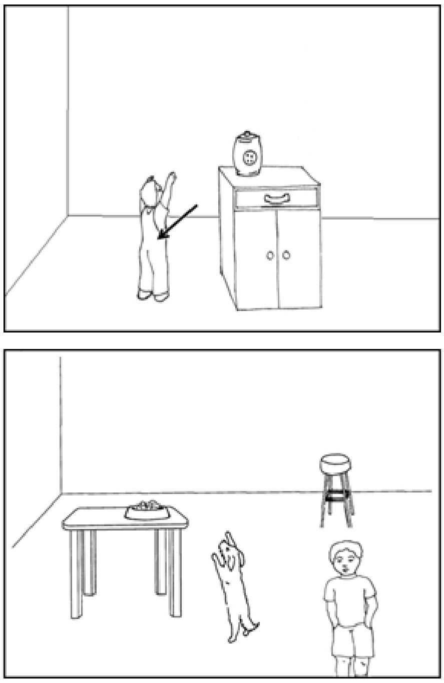
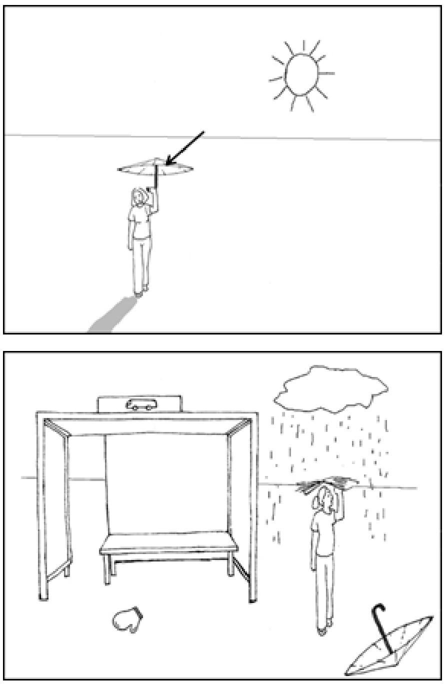
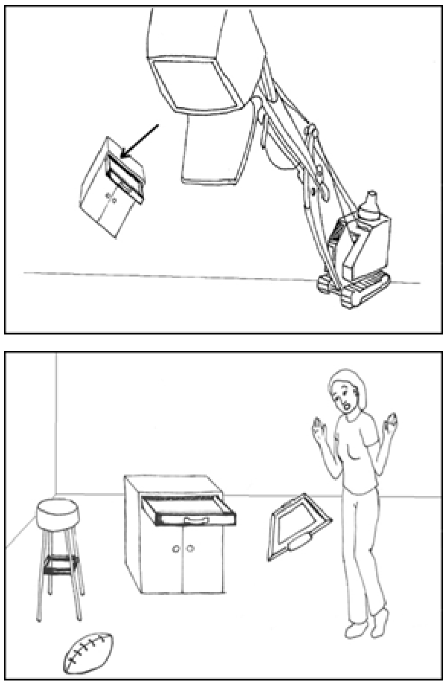
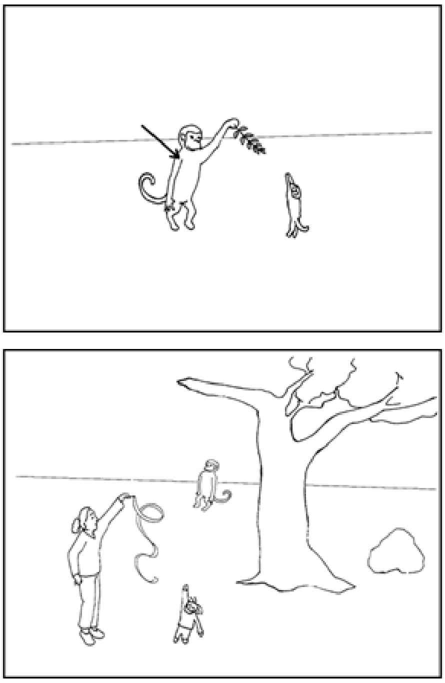


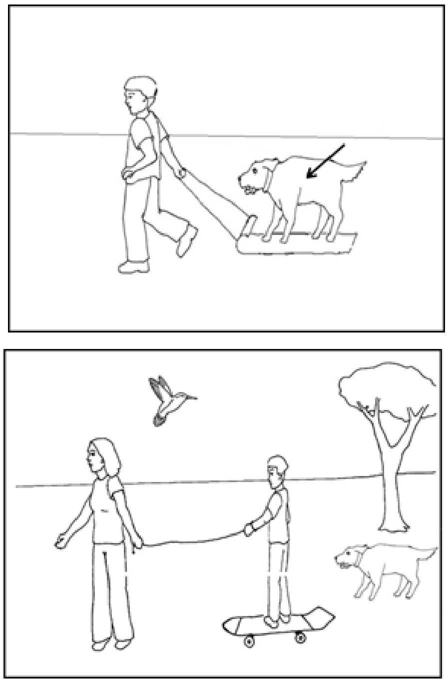


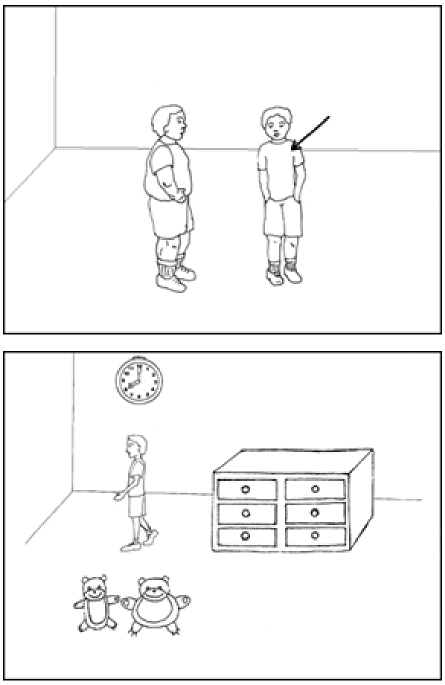




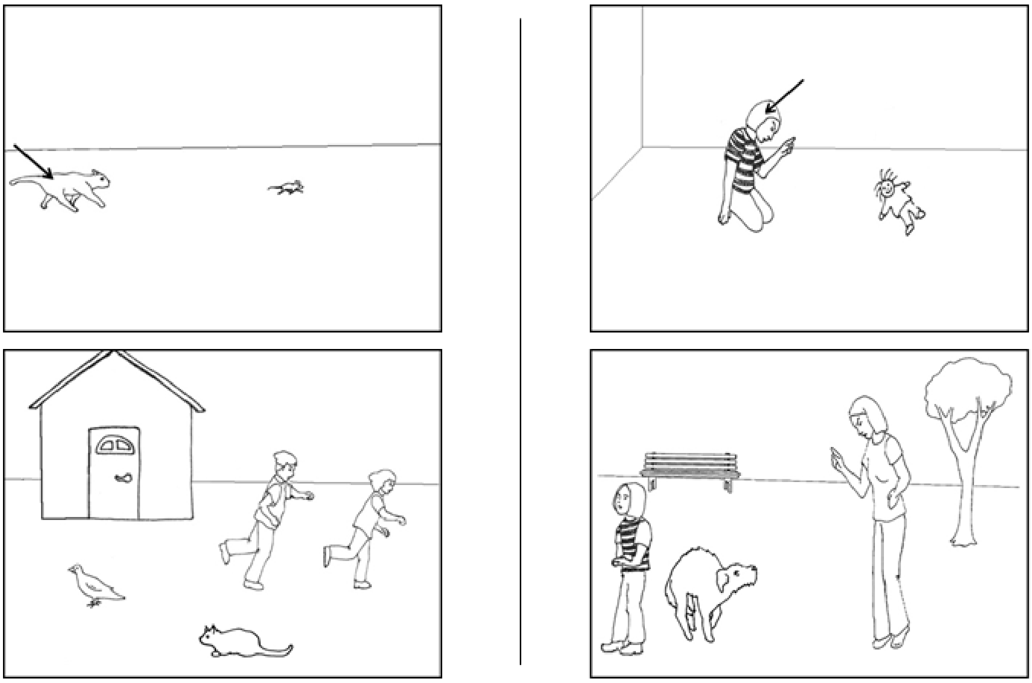
Annex A: Materials from experiment 1, chapter II

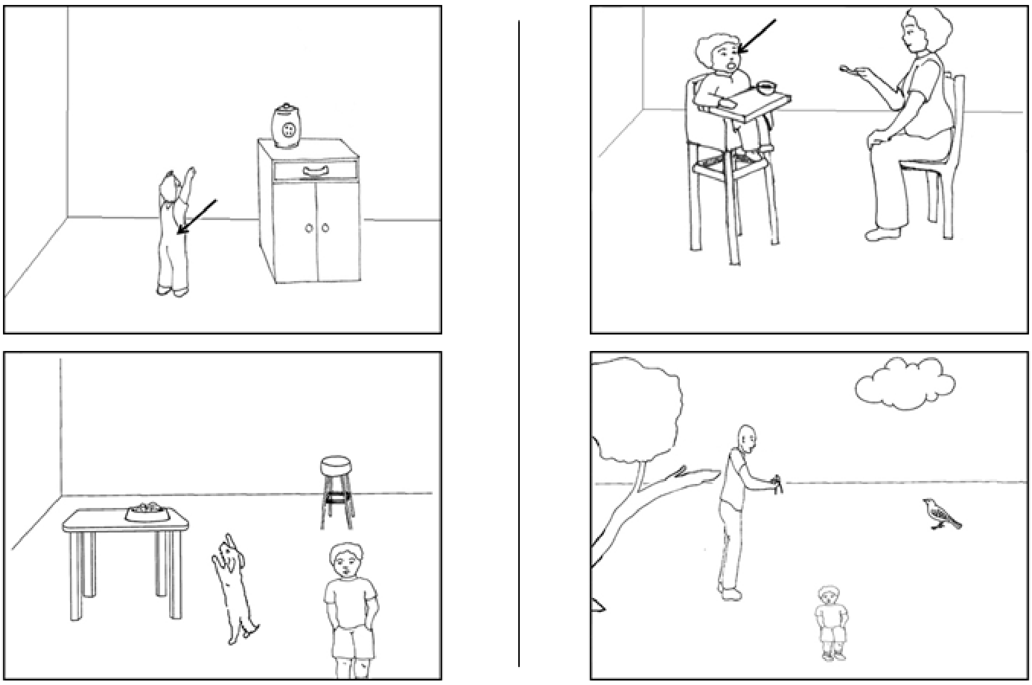




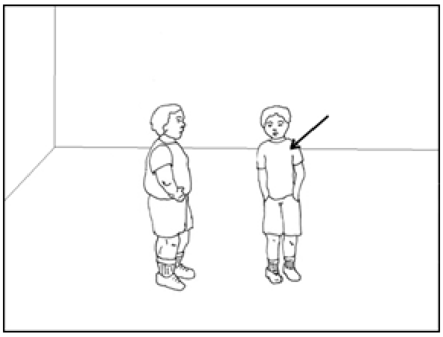


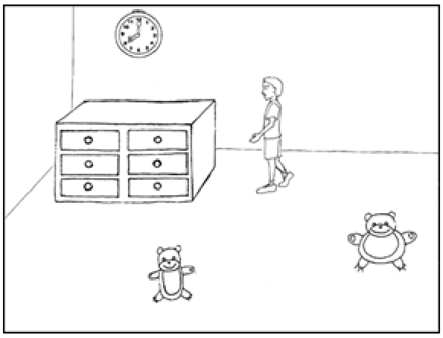
Annex B: Materials from experiment 2, chapter II
Scene Analogy task



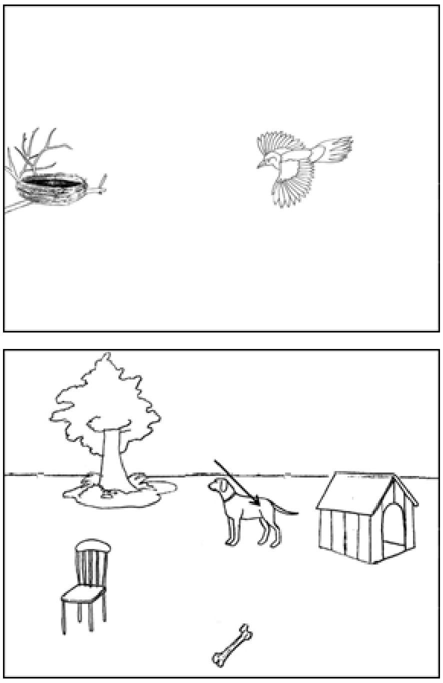


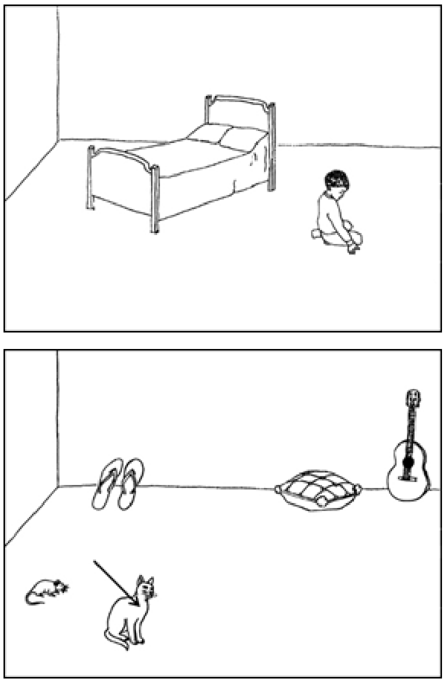
Annex B: Materials from experiment 2, chapter II
Scene Analogy task

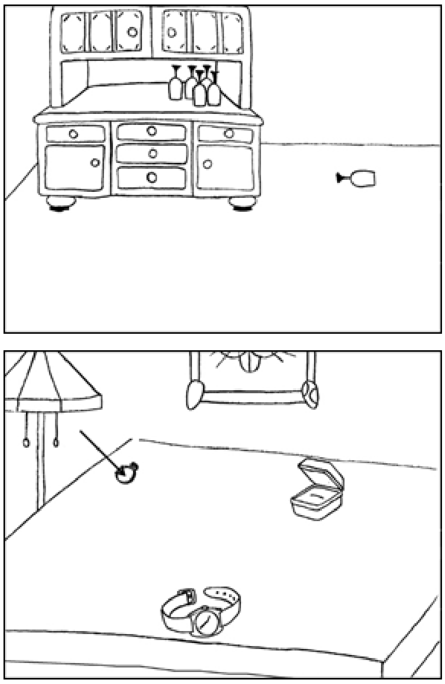




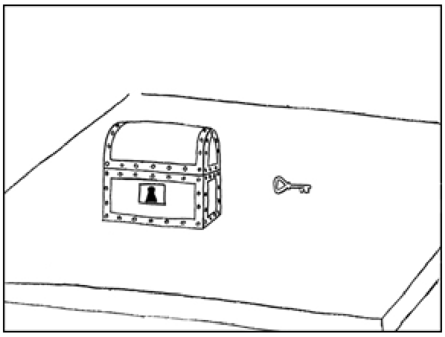
Annex B: Materials from experiment 2, chapter II
Within-Context A:B::C:? task

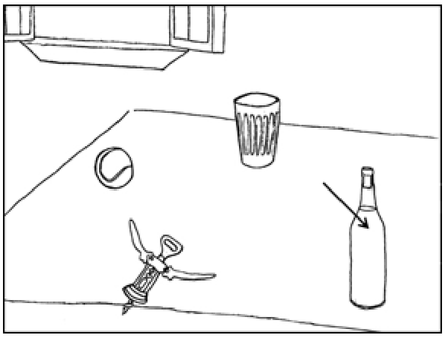




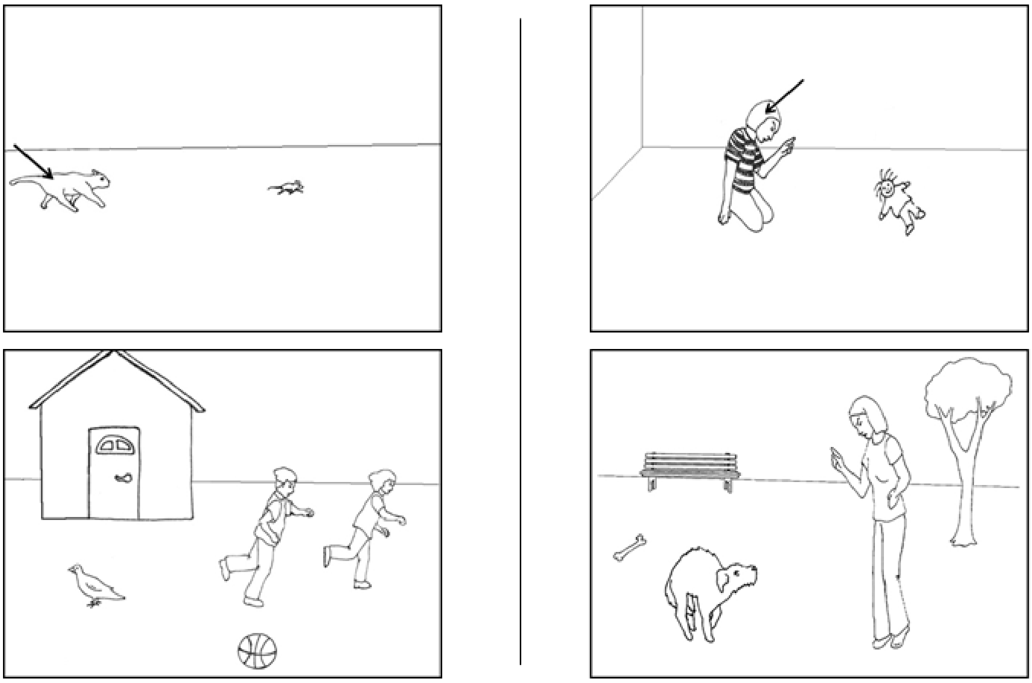


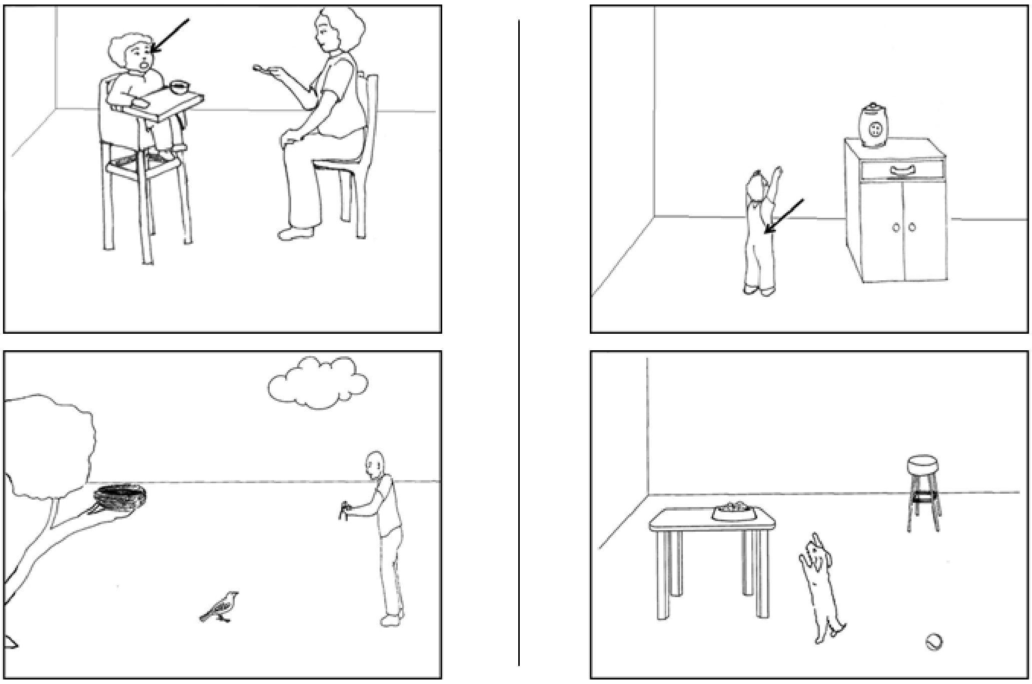
Annex B: Materials from experiment 2, chapter II
Within-Context A:B::C:? task





Annex C: Materials from experiment 3, chapter II
Scene Analogy task





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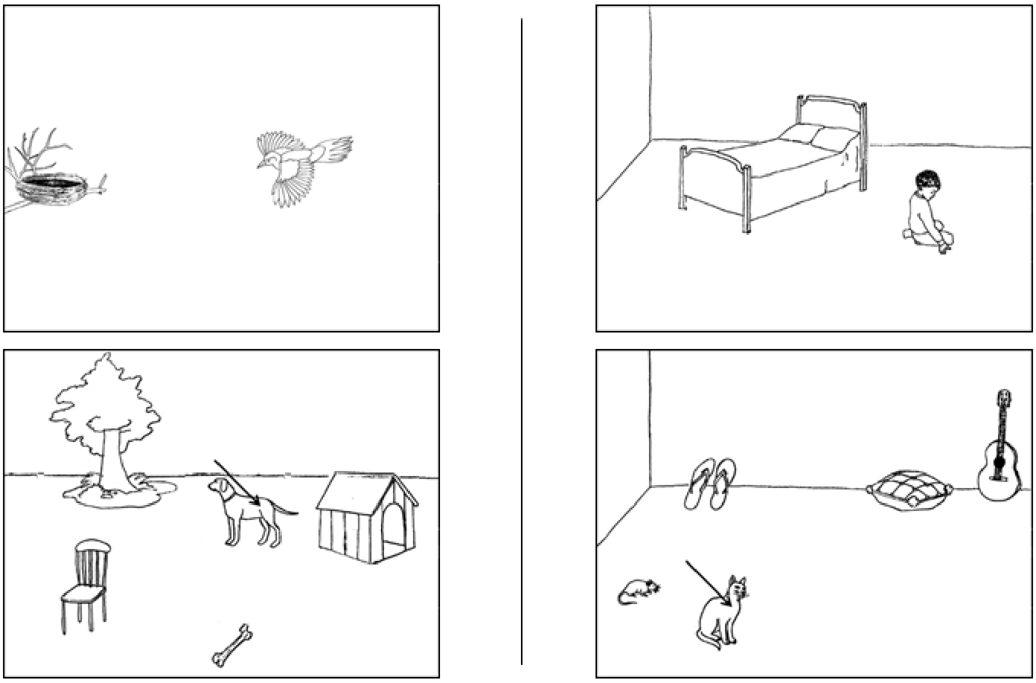
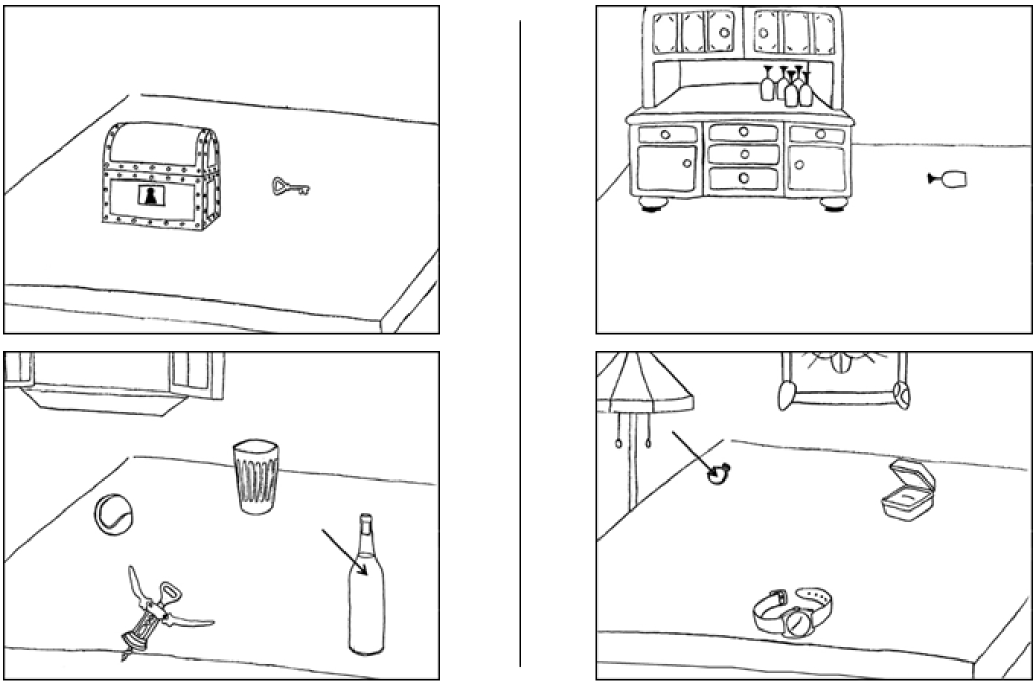
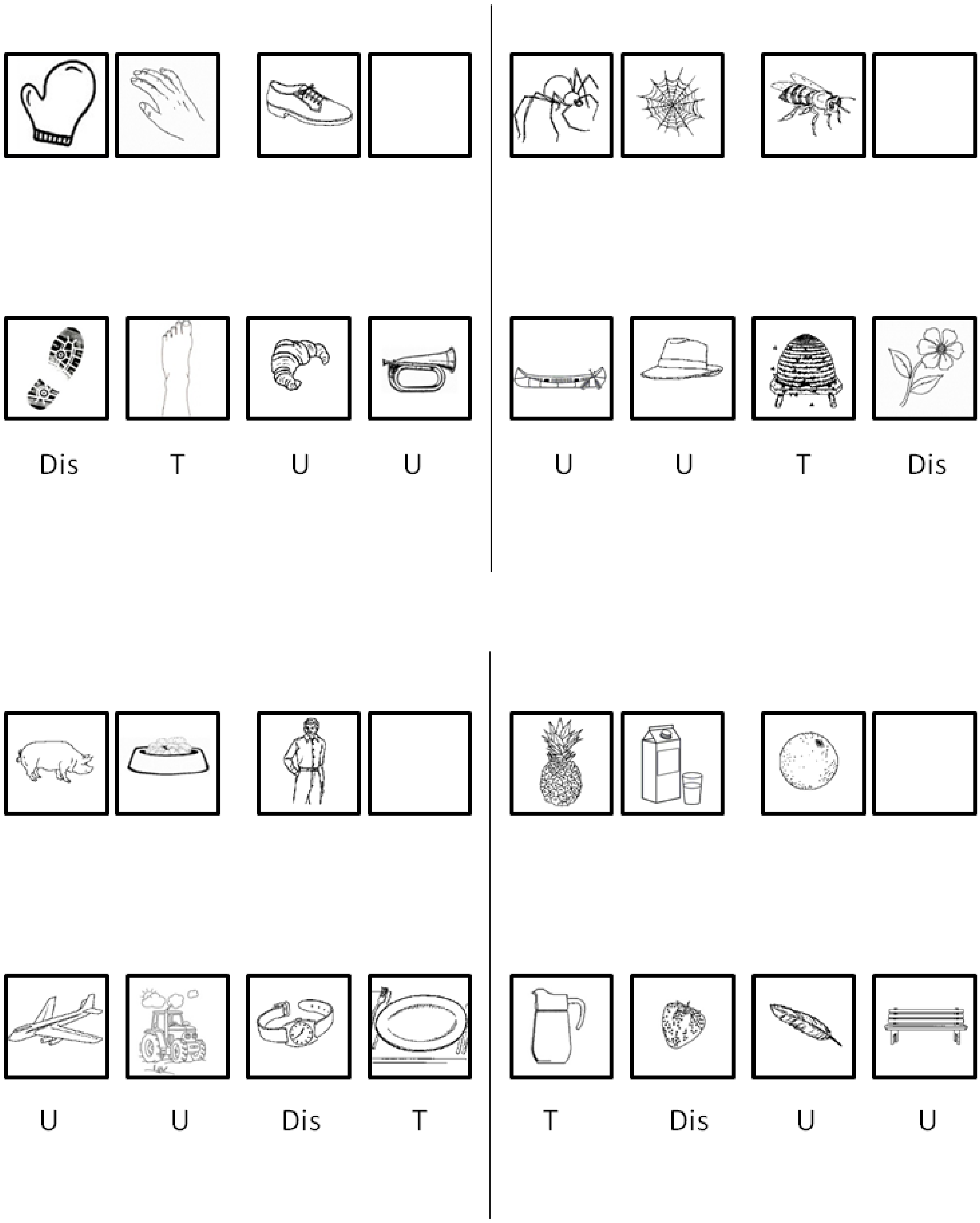
Within-Context A:B::C:? task





Annex C: Materials from experiment 3, chapter II
Standard A:B::C:? task



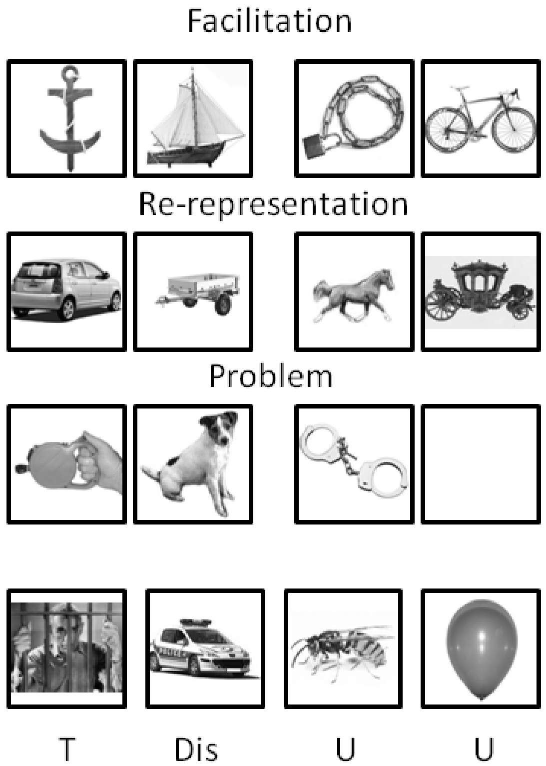
Annex D: Materials from experiment 1, chapter III

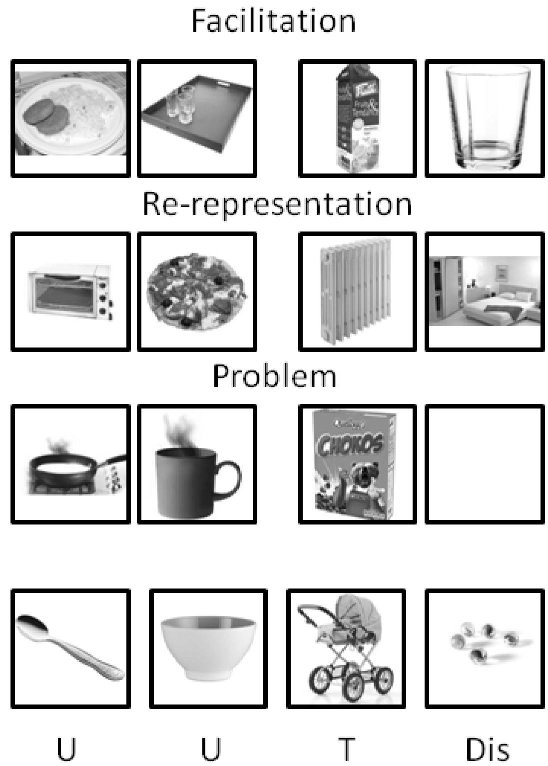
A	B	C	T	Dis		U		
violence	activité	mélancolie	humeur	cruauté	silence	crabe	banane	Difficult
vague	marée	moment	temps	lenteur	horloge	bleuet	cartable	
lampe	prise	télécommande	pile	bouton	télévision	botte	seau	
scalpel	incision	charrue	sillon	agriculture	terre	grade	naissance	
crête	onde	sommet	montagne	cime	dessus	cerveau	calembour	
tomber	gravité	éclater	pression	ballon	destruction	pilon	camion	
strophe	chanson	grain	épi	tige	blé	glue	roux	
santé	maladie	gouvernement	anarchie	démocratie	trouble	jasmin	larve	
robe	cintre	veste	patère	pullover	manche	saucisse	crapaud	
médias	nouvelles	gouvernement	lois	peuple	république	particule	émulsion	
plume	oiseau	écaille	poisson	argenté	aquatique	châtaigne	tache	Easy
oiseau	nid	chien	niche	os	laisse	casserole	pomme	
cou	écharpe	main	gant	doigt	ongle	rage	vent	
yeux	voir	nez	sentir	mouchoir	narine	croquette	grenade	
viande	boucherie	pain	boulangerie	baguette	farine	dragon	ballon	
tuiles	toit	briques	mur	ciment	béton	nuage	agneau	
pluie	goutte	neige	flocon	ski	blanc	cri	pavé	
poule	poussin	cheval	poulain	selle	étable	pantalon	imprimante	
infirmière	hôpital	avocat	tribunal	justice	plainte	souris	volcan	
vache	lait	poule	œuf	crête	renard	camembert	voiture	

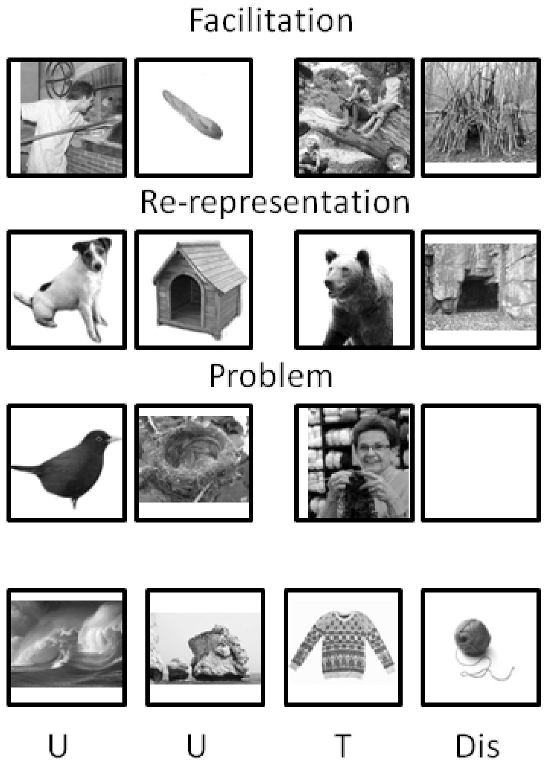
Annex E: Materials from experiment 2, chapter III

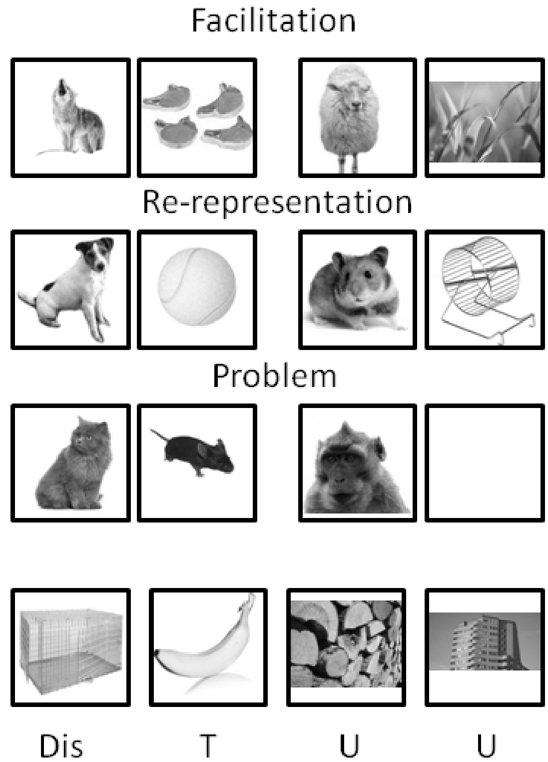
A	B	C	T	Dis Other-relation	Dis Opposite-relation	U		
abeille	ruche	nid	arbre	terrier	oiseau	silence	banane	activité
pâté	chien	souris	chat	rat	gruyère	vague	lenteur	cartable
jouet	carton	valise	soute	bagage	chemise	prise	télévision	seau
collier	bijouterie	librairie	centre commercial	bibliothèque	livre	scalpel	charrue	naissance
fourchette	cuisine	salon	maison	salle à manger	canapé	crête	cerveau	onde
narine	nez	museau	cerf	respiration	naseau	gravité	ballon	camion
croquettes	gamelle	bol	armoire	couverts	céréales	tige	sommet	glue
pied	enfant	éléphant	écosystème	hippopotame	patte	santé	gouvernem ent	jasmin
grotte	ours	chien	tique	laisse	niche	robe	crapaud	cintre
livre	chapitre	acte	scène	comédien	pièce	lois	particule	peuple
chanson	strophe	épi	grain	feuille	plante	tache	écaille	plume
blé	pain	vin	ébriété	bière	raisin	casserole	os	oiseau
casserole	pâtissier	soldat	général	médaille	fusil	cou	vent	rage
orange	fruit	légume	végétaux	viande	haricots	yeux	croquette	mouchoir
cœur	tronc	tête	organisme	pied	cerveau	boucherie	pain	dragon
tuiles	toit	murs	immeuble	papier-peint	briques	nuage	agneau	nez
veste	patère	cintre	penderie	pince à linge	robe	pluie	cri	pavé
soleil	sécheresse	humidité	moisissure	salle de bain	pluie	cheval	pantalon	imprimante
sol	terreau	glace	eau	feu	banquise	hôpital	avocat	souris
train	rails	rivière	lit	fleuve	bateau	vache	œuf	musicien

Annex F: Materials from experiment 1, chapter V









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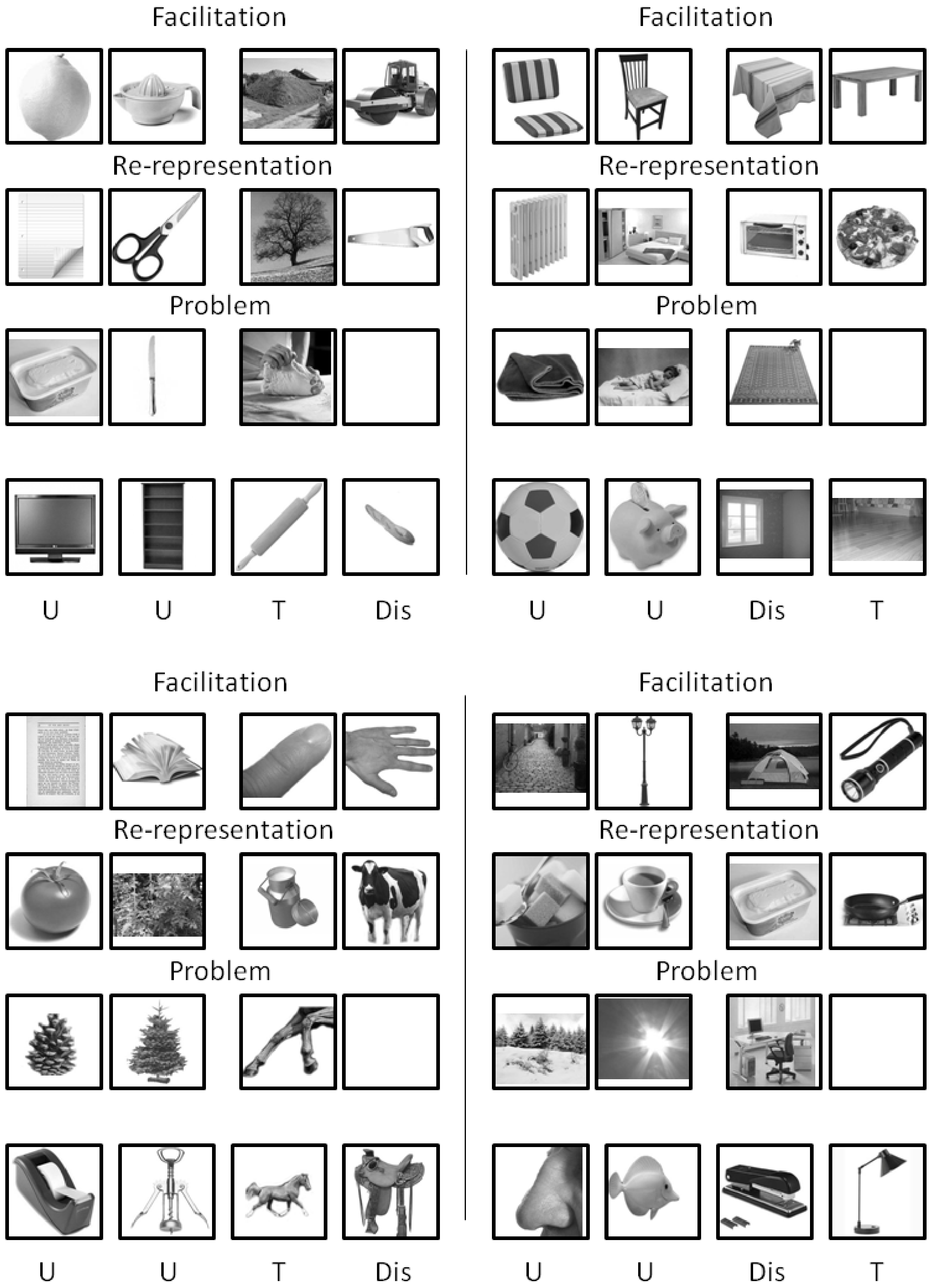
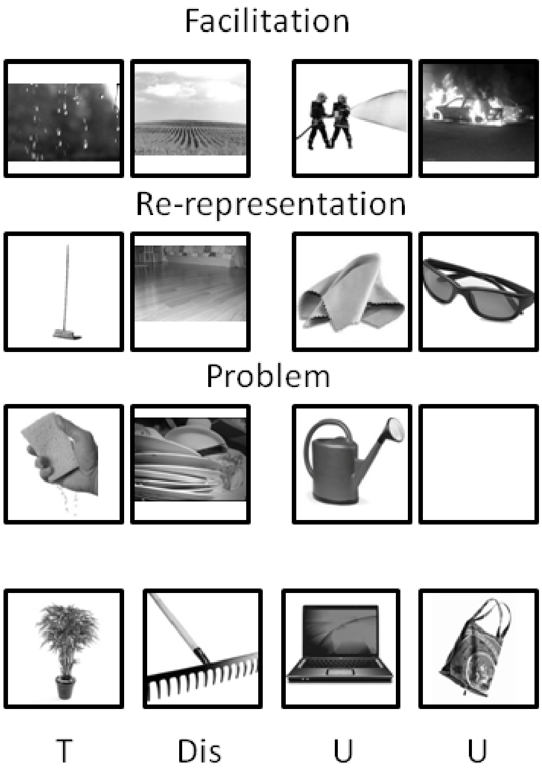
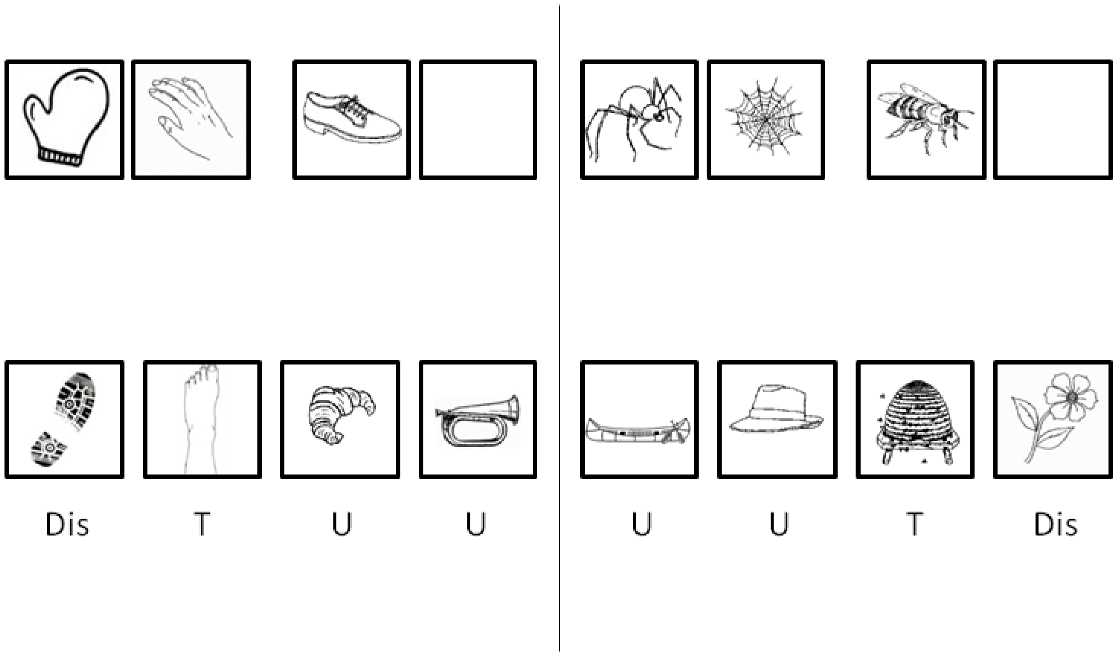
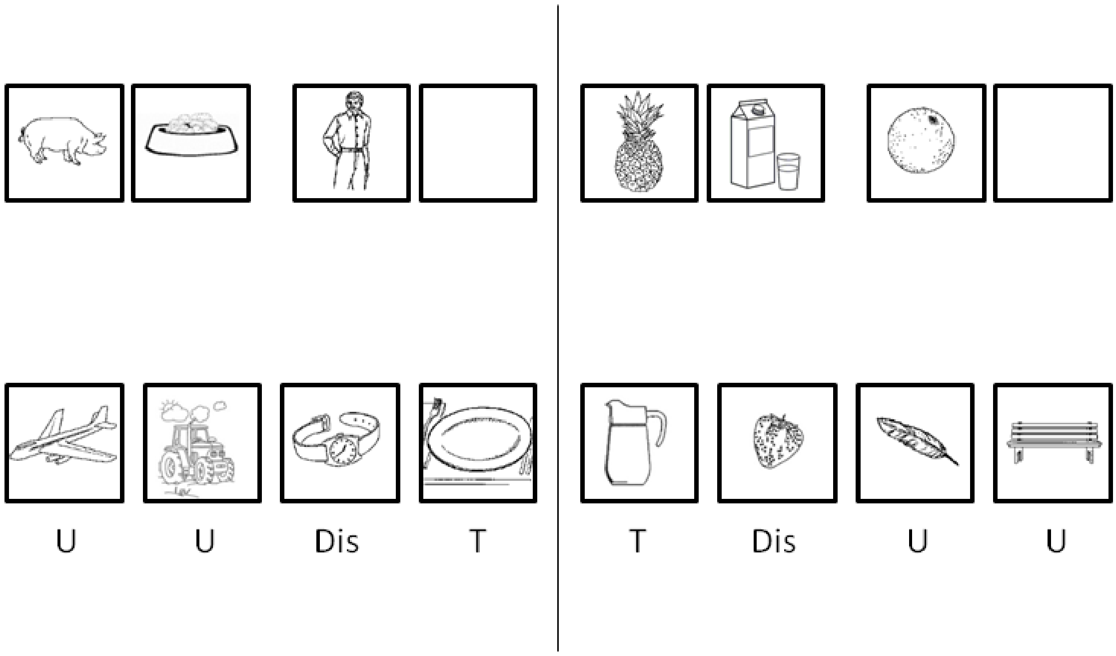


Annex F: Materials from experiment 1, chapter V



Annex G: Materials from experiment 2, chapter V





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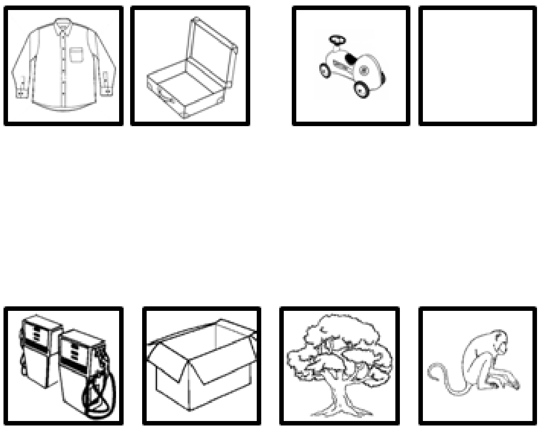

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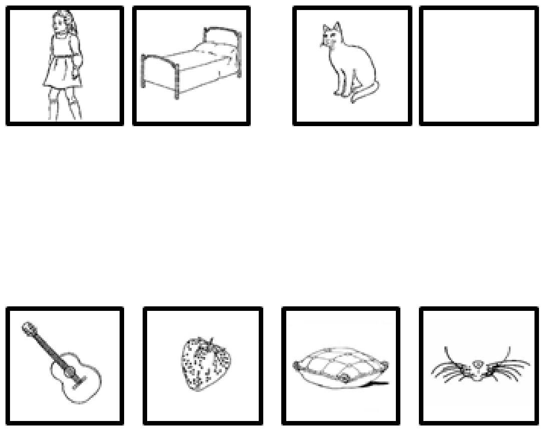

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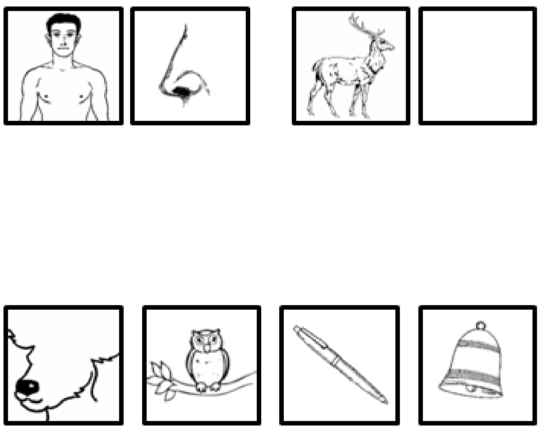

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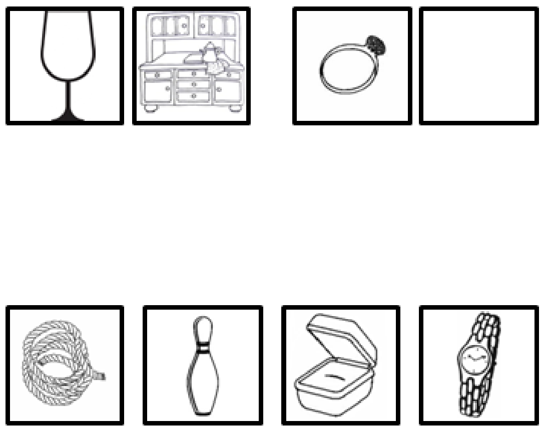

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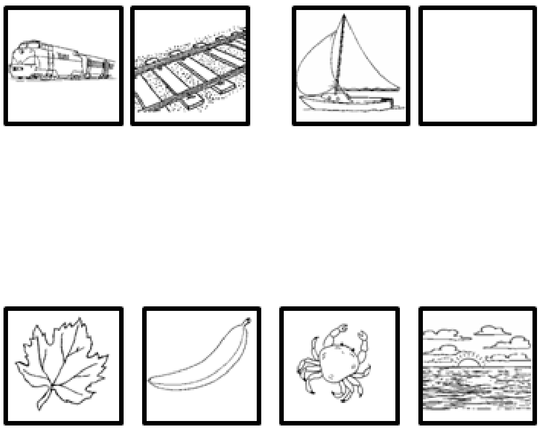

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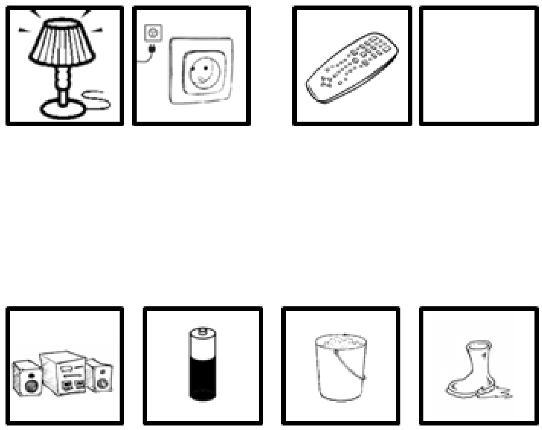

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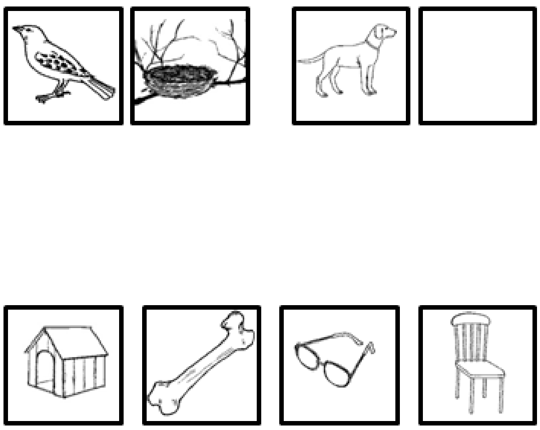

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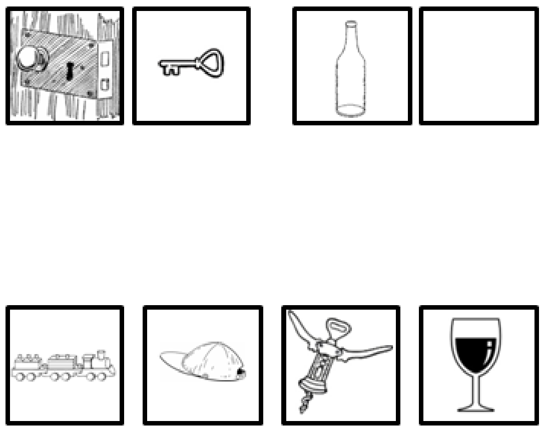

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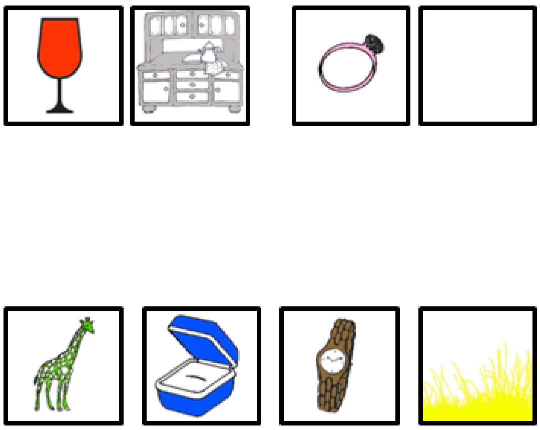

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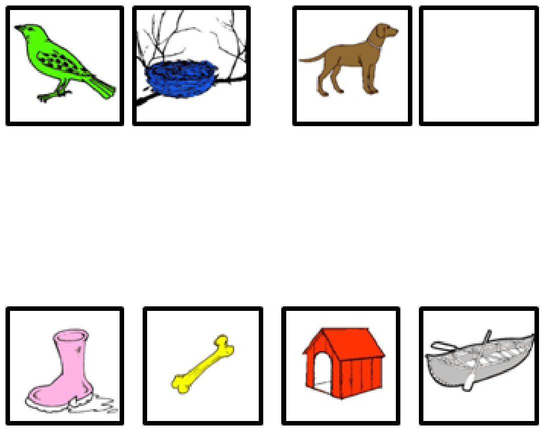
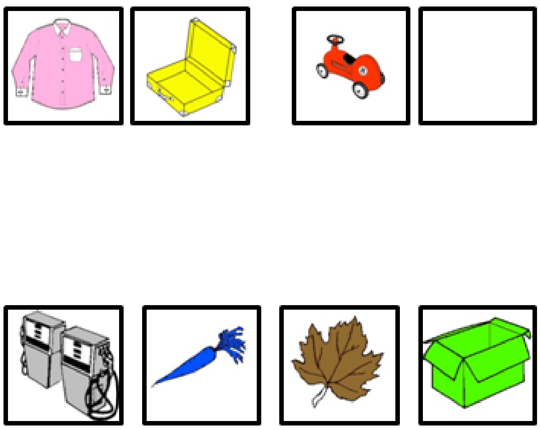
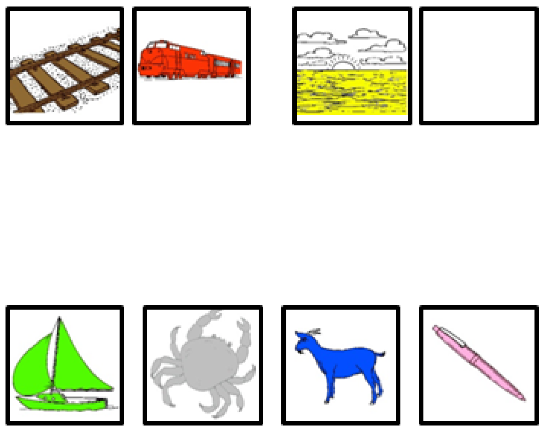


U Dis T U

Semantic trials

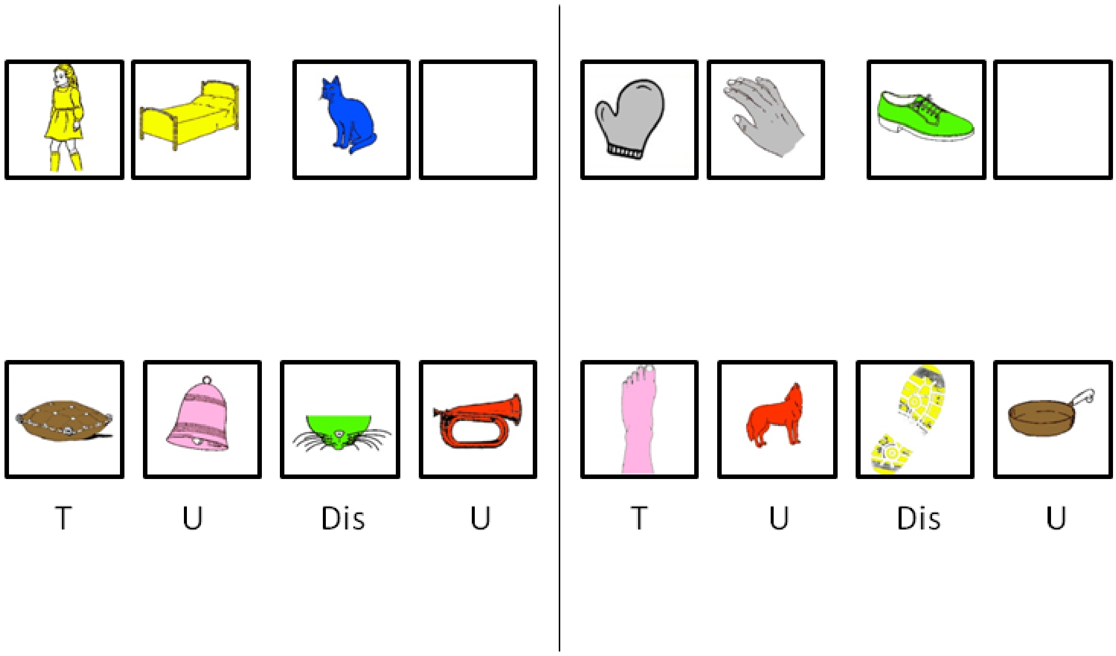


Dis U U T

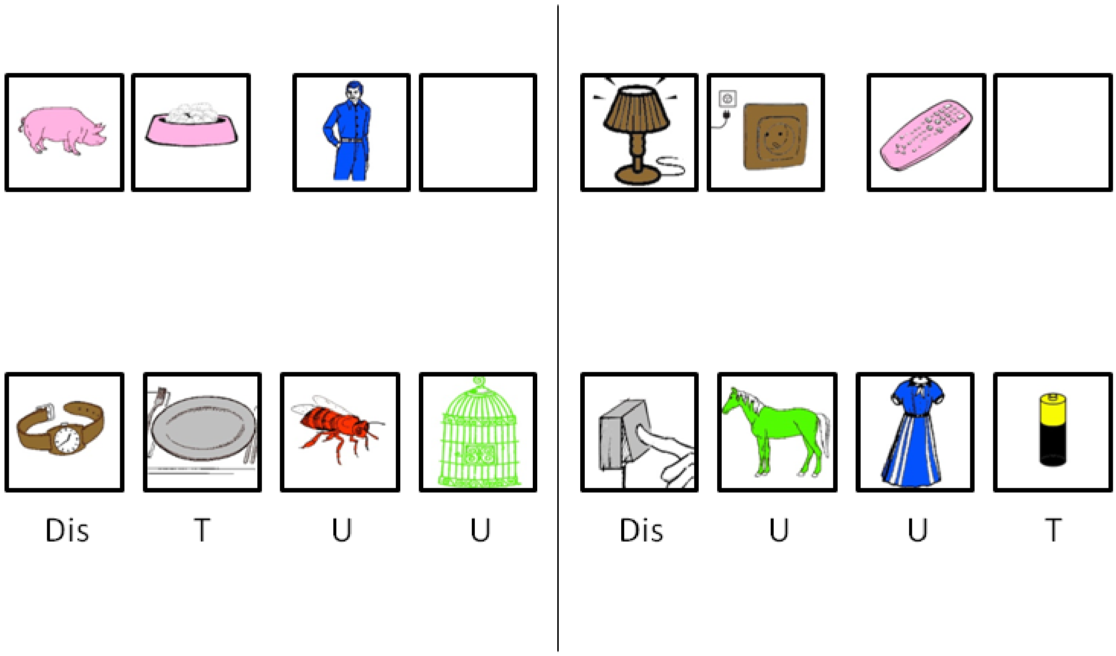


T Dis U U

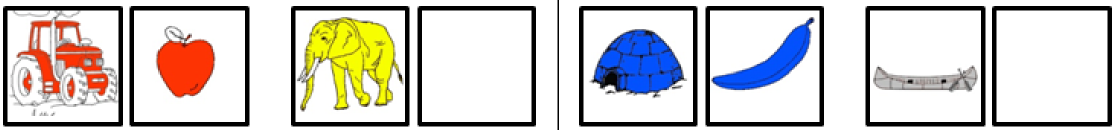
Annex H: Materials from experiment 3, chapter V

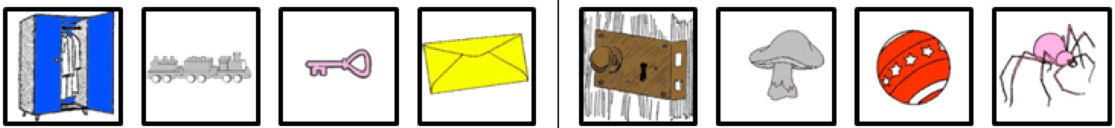


Mixed trials



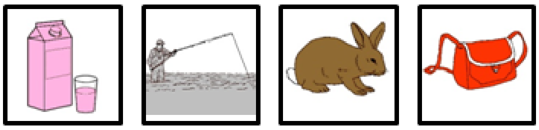
Annex H: Materials from experiment 3, chapter V





U U U T U T U U

Color trials



U U T U